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# The Banff Nappe: an interpretation of the structure of the Dalradian rocks of north-east Scotland

by H. H. READ, F.R.S.

Received 3 December 1953; read 7 May 1954

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**ABSTRACT:** The development of knowledge of the Highland Schists of north-east Scotland is reviewed and is used to present a general synthesis of the distribution and metamorphic condition of the rocks of some 2000 square miles of country. The schist-geology is interpreted as essentially controlled by the great Banff Nappe. The rocks of the Banff Division, probably the equivalents of the Upper Dalradian of Perthshire, form a tectonic sheet on the Lower Dalradian, the separation plane cropping out as the Boyne Line. Beneath the Banff Division, the Lower Dalradian is arranged in a recumbent anticline, closing south-eastwards and sliced in its upper limb by the Boyne dislocation, a lag. The core of the recumbent anticline is made of gneisses, often migmatitic in origin, above which, in the Banff Division itself, is the wide development of andalusite-cordierite-schists typical of this province and interpreted as a regional thermal zone closely connected in origin with the gneisses. The metamorphism and migmatisation are broadly later than the orogeny but it may be suggested that the gigantic movement of the gneiss core was in some way facilitated by the migmatisation of its components.

## 1. INTRODUCTION

ALTHOUGH OUR KNOWLEDGE of them is admittedly imperfect and uneven, the Highland Schists of much of the counties of Aberdeen and Banff in north-east Scotland clearly possess lithological, metamorphic and tectonic characters that distinguish them from the other Dalradian rocks of the adjacent regions to the south and west. Lithologically, they include slates, greywackes and pebbly limestones of the Greywacke facies; their metamorphism is marked by a regional development of andalusite and cordierite; structurally, they may form a much-crumpled sheet resting with some kind of discordance on a Lower Dalradian basement. Inspection of Sheet 9 of the Geological Survey Map of Scotland on the scale of 4 miles to an inch—this map including most of the ground dealt with here—immediately brings out these special features. They can be seen from Plate 1, which is based largely on the Survey Maps and those of Sir Edward Bailey and the writer.

Towards the end of the first world war, I was fortunate enough to be assigned the revision and description of one-inch Sheets 86 and 96 of the Geological Survey Map of Scotland, these sheets making some 560 square miles of the area of present interest. Since then I have returned a dozen times or more to this fascinating though tantalising ground; much of the area I have mapped in detail and all of it I have inspected and traversed. In these circumstances, I consider certain proposals concerning the general structure of north-east Scotland to be now worth making, especially as my friends Dr. O. C. Farquhar, Dr. Janet Watson and Dr. John Sutton are busy with detailed but local investigations in this region.

In the previous paragraph, this ground has been called tantalising, a description arising from the kinds of exposure available to us. There is, on the one hand, a truly magnificent coast-section, perfectly continuous over tens of miles and showing in all some fifty miles of Highland Schists. Part of this section runs across the regional strike and plunge; part along them. Against these agreeable arrangements has to be set the poorly exposed condition of much of Lower Banffshire and the Strathbogie, Buchan and Formartine districts of Aberdeenshire. Here exposures are just sufficient for the mapping of broad units, but the tracing of finer members of the schist succession, or the determination of small structures, is not possible. South-westwards, this lower country rises into the mountains of Upper Banffshire and the Aberdeenshire border, but even in these elevated regions, as also along the Don–Dee watershed, heather and peat obscure much of the rock. Detailed work in these inland parts is consequently circumscribed and must often be directed as chance affords to the study of local problems not immediately connected with the broad structure. Nevertheless, in my opinion the broad structure can be profitably discussed. I recall how the great Highland geologist, George Barrow, maintained that any fool could map exposures but only genius could decide what was between them. This may be true and, accordingly, I shall endeavour to present the evidence with as much honesty as is possible in Highland geology, trusting that a genius will eventually appear to make the ultimate arbitrament on my proposals.

The stratigraphical units in the metamorphic geology of north-east Scotland are thick, and their developments are extensive. Their primary mapping occupied members of the Geological Survey for nearly half a century. It seems best therefore to introduce what I call the Banff Nappe by presenting an annotated account of the growth of geological knowledge of the region. This having been done, we shall be in a position to discuss the validity of my interpretation.

## 2. THE DEVELOPMENT OF KNOWLEDGE OF NORTH-EAST SCOTTISH GEOLOGY

The one-inch maps of the Geological Survey of Scotland covering the area under consideration are shown in Fig. 1, with their dates and authors; the location of other researches of interest to us are also given. Here there is no need to summarise the investigations which were made earlier than 1880, the date of entry of the Geological Survey into the area. This pre-Survey work is mainly of historical interest and most of it is referred to in the relevant Survey memoirs.

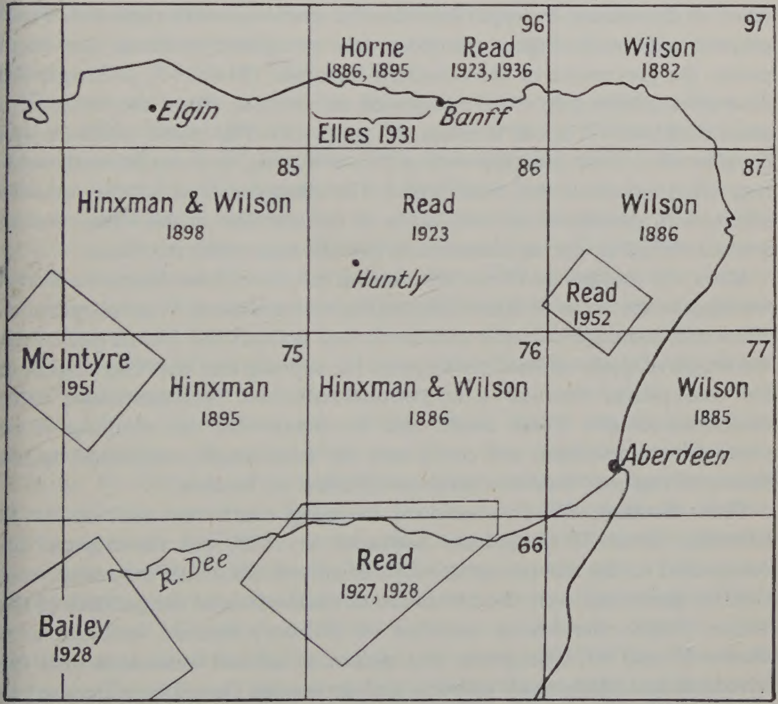


Fig. 1. Geological Survey one-inch maps, and non-Survey research areas dealing with the metamorphic rocks of north-east Scotland

Our examination proceeds clockwise from the extreme north-eastern part of the ground.

Detailed investigation began in Buchan with the publication of the Explanations of Sheet 97 (Fraserburgh) in 1882 and of Sheet 87 (Peterhead) in 1886. Both were the work of J. S. G. Wilson and were the first memoirs on Highland geology to be issued by the Survey. Wilson called the metamorphic rocks the Highland Crystalline Schists (Dalradian had not yet been invented); their age was 'not yet satisfactorily determined' but they 'probably included metamorphic Silurian Rocks' (Mem. 87, p. 7). The succession, in ascending order, was: 1, gneiss; 2, quartz-schist with quartzites; 3, knotted and andalusite-schists with calcareous beds at their base; 4, clay-slates. Passages between the members were recorded. Fine-grained beds in the higher members were recognised as being 'not at all unlike the greywacke of the Southern Uplands' (Mem. 97, p. 8) and the abundant pebbly grits were interpreted as resulting from 'the waste of a granite' (Mem. 97, pp. 8, 9; Mem. 87, pp. 9–10). The broad structure was considered to be an anticline with a NE.–SW. axis, and smaller-scale folding, often isoclinal, was established. The disappearance of the 'quartz-schists with quartzites' on both limbs of the anticline in the Ythan Valley was attributed to the replacement of the siliceous rocks by slates.

It may be interpolated here that, during this time, John Horne had been working in the areas of Sheets 86 and 96, to the west of Wilson's ground. Here andalusite-schists were well developed and in 1886 Horne dealt with the origin of these unusual rock-types. He showed that the 'clay-slates' of his area passed through a transitional zone of 'Knotenschiefer' into andalusite-schists. These could not be interpreted as resulting from contact-metamorphism and could only be 'satisfactorily explained by the theory of regional metamorphism established by Bischof'.

From Buchan, Wilson continued mapping south and west as far as Donside. Sheet 77 (Aberdeen) appeared in 1885, but no memoir accompanied it; the metamorphic rocks of almost the whole map-area were labelled gneiss and were the continuation southwards of the gneisses of the Ythan Valley, the lowest member of Wilson's Buchan succession of Sheets 87 and 97. The gneiss was shown to extend westwards into the Inverurie and Monymusk districts and across the Don–Dee watershed in Central Aberdeenshire by the work of L. W. Hinxman and J. S. G. Wilson in Sheet 76 (Map, 1886, Mem. 1890). Here the rock was described as a banded biotitic gneiss, with very occasional beds of quartzite and calcareous schist. In the Alford district the gneiss was shown to be followed northwards by an extensive group in which andalusite-schist is the dominant rock-type. This group was dealt with under the heading of 'mica, knotted, andalusite and chiastolite schists with associated clay-slates, quartzites and pebbly grits'. Its lithological and metamorphic resemblances to the higher members of Wilson's Buchan succession are obvious. Its metamorphic condition was ascribed to 'regional rather than contact metamorphism' since its distribution was not related to any visible igneous body (Mem. 76, p. 14). 'Basement beds' of pebbly quartzites and grits of this knotted schist series were described as resting on bands of gneiss at Tough, three miles south-east of Alford (Mem. 76, p. 15) and, at Mill of Brux on the Don, near the southern end of the Bogie outlier of Old Red Sandstone, a transition between the two groups was recorded—'gneiss with bands of knotted schist is found inclined at a high angle' (Mem. 76, p. 9). Again, west of the Old Red outlier, the gneiss was considered to underlie the andalusite-schists and 'the presence of incipient knots and aggregations in the gneiss at Sauchenbog, where the rock is well exposed in a deep wooded ravine, points to a gradual passage into the schists above' (Mem. 76, p. 8).

The next one-inch map to be completed by the Survey was Sheet 75 (Map, 1895, Mem. 1896), lying to the west of that just dealt with. This was the work of L. W. Hinxman. The metamorphic rocks were divided into the Cromdale Hill Series and the Banffshire Series, the latter being of greater immediate interest to us. This Banffshire Series comprised: quartzite; black schist and limestone; clay-slates and phyllites; mica-schist, andalusite-schist and kyanite-schist. This grouping was largely lithological but 'from evidence obtained elsewhere along the line of outcrop to the north and south, it is, however, probable that the quartzite is the highest member of the group, and immediately overlies the phyllite, black schist and limestone zone' (Mem. 75, p. 7). The lithological zones are repeated by 'a series of complex isoclinal folds, with a general steady dip to the east' (Mem. 75, p. 7). At this stage I would emphasise the virtual subdivision by Hinxman of his Banffshire Series into two—the composite black schist-limestone-phyllite group overlain by the quartzite. As a result, all the quartzite bodies have one side, their base, and all non-quartzite members of the Banffshire Series belonging to one group—these are propositions that are very unlikely to be true, as is suggested later. One observation of Hinxman's is of great significance: in his description of the section seen in the Muckle Fergie Burn, three miles south of Tomintoul, he recorded that 'two or three lenticular bands of calcareous quartz-hornblende-schist, containing large pebbles, occur at the base of the quartzite. This rock closely resembles the "Boulder Bed" found at the base of the quartzite in Perthshire and Argyle. . . . The schist contains fragments of dolomitic limestone, sometimes large and irregular in shape, sometimes drawn out into lenticles; and also rounded pebbles of a reddish granite with blue quartz' (Mem. 75, pp. 9–10). These exposures were described in more detail by J. W. Gregory (1931, pp. 134–5) who concluded, however, that the boulder-bed was not on the horizon of the Schichallion Boulder

Bed of Perthshire. Along the eastern border of Sheet 75, south of the Buck of the Cabrach, Hinxman remarked that the mica-schist there occurring was 'somewhat different from and more homogeneous than the schistose rocks farther to the west' (Mem. 75, p. 15); this mica-schist is the continuation westwards of the gneisses already noted as occurring west of the Bogie Old Red outlier in Sheet 76. It was stated by Hinxman to be 'sometimes very coarse-grained, and gneissose in character. Segregation-veins and strings of quartz, sometimes glassy-clear, are frequent' (Mem. 75, p. 15). Lenticular bands of quartz-schist and quartzite occur in the schist which between the Kindie and the Bucket 'passes into a gnarled granitoid gneiss containing large garnets'; farther south, on Donside, the gneiss is described as a coarse garnet-oligoclase-biotite-gneiss with accessory andalusite and sillimanite. I regard it as reasonable to consider these gneisses as the natural continuation westwards of the Donside gneiss of Sheet 76 which, as we have seen, is equivalent to the lowest division of Wilson's original Buchan succession. It is obvious too from Hinxman's description that these gneisses might well be migmatitic in origin. East and north of this particular group of schists and gneisses, andalusite-schists form the Buck of the Cabrach and are clearly the continuation of similar rocks already noted as occurring above the gneiss on the west of the Bogie Old Red outlier in Sheet 76. The boundary line between gneiss and this andalusite-schist group was not indicated in the Survey Sheet 75, but I schematically inserted it on Sheet 9 of the quarter-mile map when this was being prepared, and it is shown in Plate 1. Hinxman recorded andalusite-schists on Meikle Firbriggs, north-west of the Cabrach outlier of Old Red Sandstone. Recently I have inspected these schists and found them to be best interpreted as occupying a horizon quite different from that of the Buck andalusite-schists; this matter is referred to later.

This is, perhaps, the most appropriate place to mention the recent re-investigation by D. B. McIntyre (1952) of a portion of Sheet 75, especially in the Tomintoul and Cromdale Hills areas—though it is true that this ground is a long way west of the proposed Banff Nappe. McIntyre showed that the Moine granulites, the rocks of their eastern border or the Cromdale Hills Series, and the Dalradian schists, limestones and quartzites (belonging to Hinxman's Banffshire Series) are homoaxial. 'Both series (i.e. Moine and Dalradian) have suffered the same movement; namely, north-east to south-west in direction, and apparently in general of the upper layers towards the south-west relative to the lower' (McIntyre, 1952, p. 16). McIntyre showed that many of the contacts between rock-groups are not stratigraphical but tectonic. Thus, the Cnoc Lochy quartzite north of Tomintoul 'is a gigantic flake of Moine rising into the overlying graphite-schist of the Dalradian. . . . The pinched-off nose of the Cnoc Lochy quartzite . . . is interpreted as a tectonic inclusion ("fish") of Moine now entirely enclosed by Dalradian rocks. . . . Possibly many of the other "Dalradian" quartzites represent similar tectonic inclusions' (McIntyre, 1952, p. 15). This modern work of McIntyre's certainly adds to the entertainment value of any Banff Nappe.

After the completion of Sheets 75 and 76, Hinxman and Wilson were associated in Sheet 85, an area to the north, the map appearing in 1898 and the explanatory Memoir in 1902, with petrology by J. S. Flett. The western portion of the area shown in the Sheet is occupied by siliceous granulites and mica-schists similar to those of the Cromdale Hill Series of the country to the south, represented in Sheet 75. These were now called the Central Highland Granulites and equated with the Moine rocks of the northern Highlands. (Mem. 85, pp. 10, 24). The eastern part of the area shown in the Sheet is composed of the Banffshire Series, continuing north-eastwards from the area of Sheet 75. This Series was now recognised as part of the Dalradian; 'these quartzites, schists and limestones represent a portion of the belt of more or less altered sedimentary rocks with associated igneous intrusions which extends almost continuously across Scotland from the south-west of Argyllshire to the Moray Firth' (Mem. 85, p. 10). The many quartzite belts with north-east to south-west trend, and the lenses of quartzite in the Banffshire Series, were considered to be 'more than probably' only one zone of quartzite repeated by isoclinal folding (Mem. 85, p. 12). 'In this Sheet there is no direct evidence that the quartzite rests unconformably on the other members of the Banffshire Series. The indirect evidence is very strong' (Mem. 85, p. 12) because the main belt of quartzite is in contact at various points with phyllite, black schist and limestone. All members of the Banffshire Series had been affected by a common system of folding. Most of the quartzites were granulitic but, in the south-east corner of the map in the Cabrach, pebbly grits occurred. In this quarter, on Black Hill, 'a local base to the quartzite is indicated by the coarse pebbly grit, almost a conglomerate'; 'the well-rounded pebbles are sometimes as much as 4 or 5 inches in diameter and are chiefly composed of white quartzite, suggesting that this rock is due to local erosion' (Mem. 85, p. 16). North of Black Hill, a narrow, much-folded, belt of quartzite (pebbly grit on Sheet 9 of the quarter-mile map) separated 'the black schist and the phyllites' (Mem. 85, p. 16). The phyllites here concerned are, as I show immediately, an extension of the great andalusite-schist group of the country to the east, represented in Sheet 86. It will be shown, too, that other phyllites of the area of Sheet 85 are extensions of certain other stratigraphical groups of the area shown in Sheet 86 and it becomes clear, as was to be expected, that the simple lithological divisions adopted by Hinxman and Wilson for their ground include many different stratigraphical groups. Attention should be directed to the care with which these workers mapped the belt of limestone that is seen to run north-eastward across the map through Dufftown. This limestone continues south-westwards to Glen Livet in Sheet 75 and, as we now know, north-eastwards through the area of Sheet 86 to the Banffshire coast in the area of Sheet 96. It makes one of the most important and significant markers in the Dalradian succession of north-east Scotland.

The Survey investigation of the main area of the proposed Banff Nappe was completed, after an interval of twenty years, by the publication in 1923 of Sheets 86 and 96, and the explanatory Memoir, *The Geology of Banff, Huntly and Turriff.* The ground had been mapped by Horne some forty years before but no explanations had appeared; it fell to me to map the area and to describe its geology. The Highland Schists are magnificently exposed in the practically continuous Banffshire Coast-section trending across the strike. Since the landward parts of the areas covered by these two Sheets are no better exposed than the rest of north-east Scotland, this is a fortunate circumstance—indeed, it is likely that the course of north-east Scottish geology would have been rather different if this splendid section had been investigated first and the divisions so established had then

TABLE I: **The Banffshire Coast-section.** (Mem. 86 and 96, 1923)

| | |
|---|---|
| BANFF DIVISION | n. *Macduff Group:* slate, greywacke and pebbly grit. |
| | m. *Boyndie Bay Group:* andalusite-schist and pebbly grit. |
| | l. *Whitehills Group:* rapid alternations of pebbly grit, pebbly limestone, flags, phyllite, limestone, etc. |
| | k. *Boyne Limestone:* thick limestone and subordinate mica-schists and phyllites. |
| THE BOYNE LINE: a line of discontinuity along which, inland, groups *j* and *k*, *j* and *l*, *j* and *m*, *h* and *m* are brought into conjunction. | |
| KEITH DIVISION | j. *Cowhythe Gneiss:* biotite-gneiss with occasional cordierite- or sillimanite-gneiss, and a thin limestone band. |
| | h. *Portsoy Group:* mica-schist, graphite-schist, tremolitic limestone, quartzite and transitions between these. |
| | g. *Durn Hill Quartzite:* quartzite and quartzose gneiss. |
| | f. *Sandend Group:* limestone, black schist, staurolite-schist and mica-schist. |
| | e. *Garron Point Group:* actinolite-schists, silvery mica-schists. |
| | d. *Crathie Point Group:* calc-biotite-flags. |
| | c. *Findlater Flags:* muscovite-biotite-flags with scarce quartzite. |
| | b. *West Sands Group:* garnetiferous mica-schist with a thin calcareous band. |
| | a. *Cullen Quartzite:* granulitic quartzites, with subordinate garnetiferous mica-schists. |

been traced inland. But the areas of the one-inch map-sheets are rectangular and the official mind is often as rigidly confined.

The Highland Schists of the Banffshire Coast-section were divided by me into two great divisions, the Keith Division, considered to be traceable across Scotland to Argyllshire, and the Banff Division, considered to be confined to north-east Scotland (Mem. 86 and 96, pp. 5, 11–72). It was suggested that the two divisions were separated by a plane of discontinuity, possibly 'a folded thrust-plane' (*loc. cit.*, pp. 5, 46) or 'one along which something of the nature of thrusting has occurred, rather than one of unconformity' (*loc. cit.*, p. 68) and the trace of this plane on the ground was called the Boyne Line. The Banff Division was arranged in a broad synclinal fold—the Turriff Syncline—which followed to the west the Buchan Anticline already mentioned.

Table I gives the classification and lithology of the Highland Schists of the coast-section. I considered that there were no breaks within each of the two main divisions (Mem. 86 and 96, pp. 5–6). It was noted that as they were followed inland, groups *c*, *d* and *e* of this succession were represented by flags of Findlater type. Typical minerals of the appropriate members of the Keith Division were garnet, staurolite, kyanite, sillimanite and cordierite; in the Banff Division, andalusite and cordierite were characteristic, but were also accompanied by sillimanite, staurolite and garnet.

I showed that pelitic rocks with abundant andalusite—the Boyndie Bay Group—were spectacularly developed in the Banffshire Coast-section. In the Fyvie district in the south-eastern corner of Sheet 86 there was another spread of andalusite-schists—the Fyvie Schists—which bore similar relations to the Macduff Group as the Boyndie Bay Group does, in that they both pass gradually into the slate facies. 'It appears extremely probable that the Boyndie Bay Group continues from the Bogie Valley by the Buck of the Cabrach and Correen Hills into the Fyvie area of Fyvie Schists and thence north-north-eastwards to the Buchan coast to the west of Fraserburgh, and consequently that the great area of the Macduff Group is followed outwards in all directions by a belt of rocks of one type, a point of some importance for the structure and metamorphism of the Banff Division as a whole' (Mem. 86 and 96, p. 55). From the geometry of faulting of known throw in the Fyvie area, I concluded that the andalusite-schists underlay the slates, and the general dip of the plane separating the two metamorphic types was low (*loc. cit.*, p. 75). These deductions were considered to be 'in agreement with the observed increase of metamorphism from the central area of Macduff Slates outwards in all directions', and it was concluded 'that the Macduff Group occupies the centre of a syncline of complex character' (*loc. cit.*, p. 75). This is the Turriff Syncline already mentioned. I agreed that the 'Boyndie Bay Group and the Fyvie Schists differ from the Macduff Group only in their metamorphic condition, but nevertheless, in addition to their lithological importance, they appear to have a certain structural value which may justify this stratigraphical treatment of metamorphic zones' (*loc. cit.*, p. 62). Now, thirty years later, and with a better appreciation of the dimension of time in metamorphic geology, I can develop this suggestion, as I do on a subsequent page.

The origin of the andalusite-schists was discussed (Mem. 86 and 96, pp. 76–7). No pre-metamorphism igneous rocks were suitably placed to give rise to these schists as a kind of gigantic thermal aureole; they were clearly earlier than the intrusion of the great gabbro sheets of the north-east Scottish province, because they were contact-metamorphosed by these sheets. From a consideration of the structural relations between the slates and the andalusite-schists in the Turriff Syncline, I suggested that depth of

TABLE II: **Banffshire–Perthshire Correlations**

| BANFFSHIRE COAST-SECTION (Read, Mem. 86 and 96, 1923) | PERTHSHIRE (Read, Mem. 86 and 96, 1923) | PERTHSHIRE (Horne, in Read, Mem. 86 and 96, 1923) | PERTHSHIRE (Elles, 1931) |
|---|---|---|---|
| n. Macduff Group | | Aberfoyle Slates | |
| m. Boyndie Bay Group | | Ben Ledi Grits | |
| l. Whitehills Group | | Pitlochry Schists | |
| k. Boyne Limestone | | Loch Tay Limestone | Loch Tay Limestone |
| THE BOYNE LINE | | FAULT | BOYNE THRUST |
| j. Cowhythe Gneiss | Ben Lawers Group | | Ben Lui Schists<br>Sron Bheag Schists |
| | | | PORTSOY THRUST |
| h. Portsoy Group | Ben Eagach Group | | Ben Lawers Schists<br>Ben Eagach Schists |
| g. Durn Hill Quartzite | Central Highland Quartzite | | C. Perthshire Quartzite |
| f. Sandend Group | Blair Atholl Series | | Blair Atholl Group |
| e. Garron Point Group | | | |
| d. Crathie Point Group | | | |
| c. Findlater Flags | | | (Leven Schists) |
| b. West Sands Group | | | |
| a. Cullen Quartzite | | | (Glen Coe Quartzite) |

burial controlled the production of the higher-grade metamorphic types. The problem of the relation between regional metamorphism, small-scale folding and the production of the broad Turriff Syncline was left open.

As has already been mentioned, I considered that the Keith Division was traceable south-south-westwards from the Banffshire coast to Perthshire and that major correlations, as set out in Table II, could be proposed. I maintained that the two sides of the Durn Hill Quartzite were different and in this I did not agree with Hinxman and Wilson who, as already mentioned, thought that in the areas of Sheets 85 and 75 the quartzite might be unconformable on the remainder of the Banffshire Series. As a consequence of this divergence of opinion, different groups of flags and mica-schists that had been subdivided on the coast run into the one comprehensive 'slate and phyllite' group of Hinxman and Wilson's ground. It may be stated that the interbedded stratigraphical position of the Central Highland Quartzite and its equivalents is now accepted by all Highland geologists.

I believed that the Banff Division had no representatives in the Perthshire succession and thought it possible 'that the great foreign cake of Banff Division rocks lies discordantly on northern representatives of the Perthshire rocks' (Mem. 86 and 96, p. 67). Here was the germ of the idea of a Banff nappe. The Master, John Horne, did not agree with my views and suggested that my correlation of the Keith Division with the Perthshire succession could be extended to include the Banff Division also, as shown in Table II (Mem. 86 and 96, pp. 72–3). The phenomena along the Boyne Line were interpreted by Horne as due to normal faulting or lateral variation in sedimentation. It might prove to be that both Horne and I were right, Horne with regard to his correlation and I with regard to my 'great foreign cake', though the cake might yet be of good Scottish origin. These possibilities are further developed on a subsequent page.

The later investigations relevant to the present introductions to the Banff Nappe, and the regions immediately to the south of it, are all non-Survey work. It is convenient to examine these contributions by space rather than by time and thus to continue with the further exploration of the area of the proposed Banff Nappe itself. Three pieces of work, dealing in particular with the Banffshire Coast-section, have to be taken first. In 1931, Miss G. L. Elles examined this section especially with regard to the distribution of metamorphic minerals. She applied the Barrovian zones to the rocks from Banff to Findochty; from east to west, the metamorphic grade rose from the Chlorite Zone through Biotite to Garnet at the Boyne Line, where it changed abruptly to Sillimanite and thence declined westwards to Kyanite, Staurolite and finally Garnet (Elles, 1931, fig. 1). The sillimanite and cordierite in the Cowhythe Gneiss were ascribed to contact-metamorphism by an underlying sheet of Older Basic Rocks (Elles, 1931, fig. 3). With regard to structure, various minor folds were mentioned, the

Boyne Line was accepted as having 'all the appearance of a folded thrust plane' (p. 27), though not producing so great a metamorphic hiatus as I had suggested, and an additional considerable thrust—the Portsoy Thrust—was considered to separate the Portsoy and Cowhythe groups east of Portsoy (Elles, 1931, pp. 28–30, figs. 3 and 4). 'The evidence afforded by the metamorphic condition of the rocks of the Portsoy coast district and its immediate hinterland suggests that the rocks have been folded into an anticlinorium whose eastern margin is now overthrust along the Boyne Line . . . in response to powerful impulses from the south-east, there were developed anticlinal structures of a large order (probably somewhat overturned to the north-west) and . . . as the impulses continued and strengthened these were eventually ruptured by the great lines of thrusting and dislocation that are now so obvious a feature of Highland geology. . . . The Boyne Line . . . is a relatively late feature in the structural history of the area' (Elles, 1931, pp. 32–3). Elles followed Horne in correlating the Boyne Limestone with the Loch Tay Limestone of Perthshire and made certain modifications (see Table II) in my correlation of the Keith Division with its Perthshire analogues.

In J. W. Gregory's *Dalradian Geology* (1931), the rocks of the Banffshire Coast-section were classified in quite a different way from those proposed by me, Horne and Elles. Gregory split off from the Dalradian the Leny Grits and Aberfoyle Slates, and their equivalents along the Highland Border, to form a new series, the Lennoxian. This series was taken to be post-Dalradian in age, and was considered to lie unconformably on the Dalradian, the two series being subsequently squeezed together. The Lennoxian was believed to be of a lower grade of metamorphism than the Dalradian; to be cleaved but not foliated; to contain detrital chlorite and mica; to be free from epidiorite intrusions and to carry abundant Dalradian debris (Gregory, 1931, pp. 30–3). This is not the place to discuss the general validity of the Lennoxian. All I need do is to consider Gregory's identification of this series on the Banffshire coast. Here he held that the Macduff Group was Lennoxian, sharply separated from the adjacent Boyndie Bay Group and resting unconformably on various Dalradian members along much of my Boyne Line (*loc. cit.*, p. 127). He stated: 'Read regards the Boyndie Bay beds as passing gradually into the Macduff group, but I have failed to confirm this conclusion' (*loc. cit.*, p. 127). Later, I (Read, 1935A, p. 23) reaffirmed the reality of this transition, somewhat brutally remarking that I could convince anyone of it in half an hour on the shore at Banff, and today I reaffirm it—the same specifically characteristic original lithological types straddle the supposed Dalradian–Lennoxian boundary whilst the metamorphic grade increases slowly across it. Gregory considered that the Boyne Limestone was a local development and might 'be Upper Dalradian deposited unconformably in a hollow between the

Cowhythe Gneiss and the Whitehills Group' (*loc. cit.*, p. 126). It may turn out, as I suggest below, that the Banff Division is the equivalent of the Upper Dalradian and hence of any 'Lennoxian', but I consider the unity of the Division on the Banffshire coast to be completely established. With regard to major structures in the north-east, Gregory held that the curvature of strike in the Dalradian indicated the direction of movement: 'north of the Cairngorm and Dee Valley granites the curve of the Dalradian . . . indicates movement from the E., and the main direction for the whole of this curve is from the ESE.' (*loc. cit.*, p. 166).

About this time there were developing, especially in the hands of E. B. Bailey and the Glasgow School, the applications of original sedimentation structures to the determination of the stratigraphical order of the Highland rocks. A new era had begun in the investigation of the Highlands. These methods, based on observations of current-bedding and graded bedding, were applied to the Banffshire Coast-section (Read, 1936). Using current-bedding, I showed that, in the Keith Division, the Cullen Quartzite younged towards the south-east and synforms and antiforms in it were synclines and anticlines, a quartzite in the Findlater Flags had its younger side towards the south-east and another quartzite in the Portsoy Group had the same. I concluded that the stratigraphical order of the Keith Division began with the Cullen Quartzite at the bottom and ended with the Cowhythe Gneiss at the top. In the Banff Division, graded bedding was well developed in the Whitehills, Boyndie Bay and Macduff Groups: 'it can be observed repeatedly that the western edge of each grit band is coarsely pebbly, and that towards the east in each grit band the pebbles become finer and that at the east margin of each bed a few crystals of andalusite appear' (Read, 1936, p. 472). I demonstrated (*loc. cit.*, pp. 473–5, fig. 2) that it was possible to deduce the stratigraphical order in the completely recrystallised beds of the Boyndie Bay Group: 'the west side of each (such) bed shows little or no andalusite; towards the east in each bed, andalusite appears, first as a few crystals, then in greater abundance, till at the east margin of each band the rock is largely composed of granular andalusite.' The andalusite registered the amount of original clayey material in the bed, and the eastern side was clearly the original top of the bed. Observations in the Macduff Group agreed with these results and I concluded 'the stratigraphical order is Whitehills Group, Boyndie Bay Group, Macduff Group and the last named is the youngest. Since the Boyne Limestone is very firmly linked on to the western edge of the Whitehills Group, the stratigraphical succession in the Banff Division begins with the Boyne Limestone and passes upwards to the Macduff Group' (Read, 1936, p. 475). If these results are correct, Gregory's views on the Banffshire Coast-section are still more clearly wide of the mark.

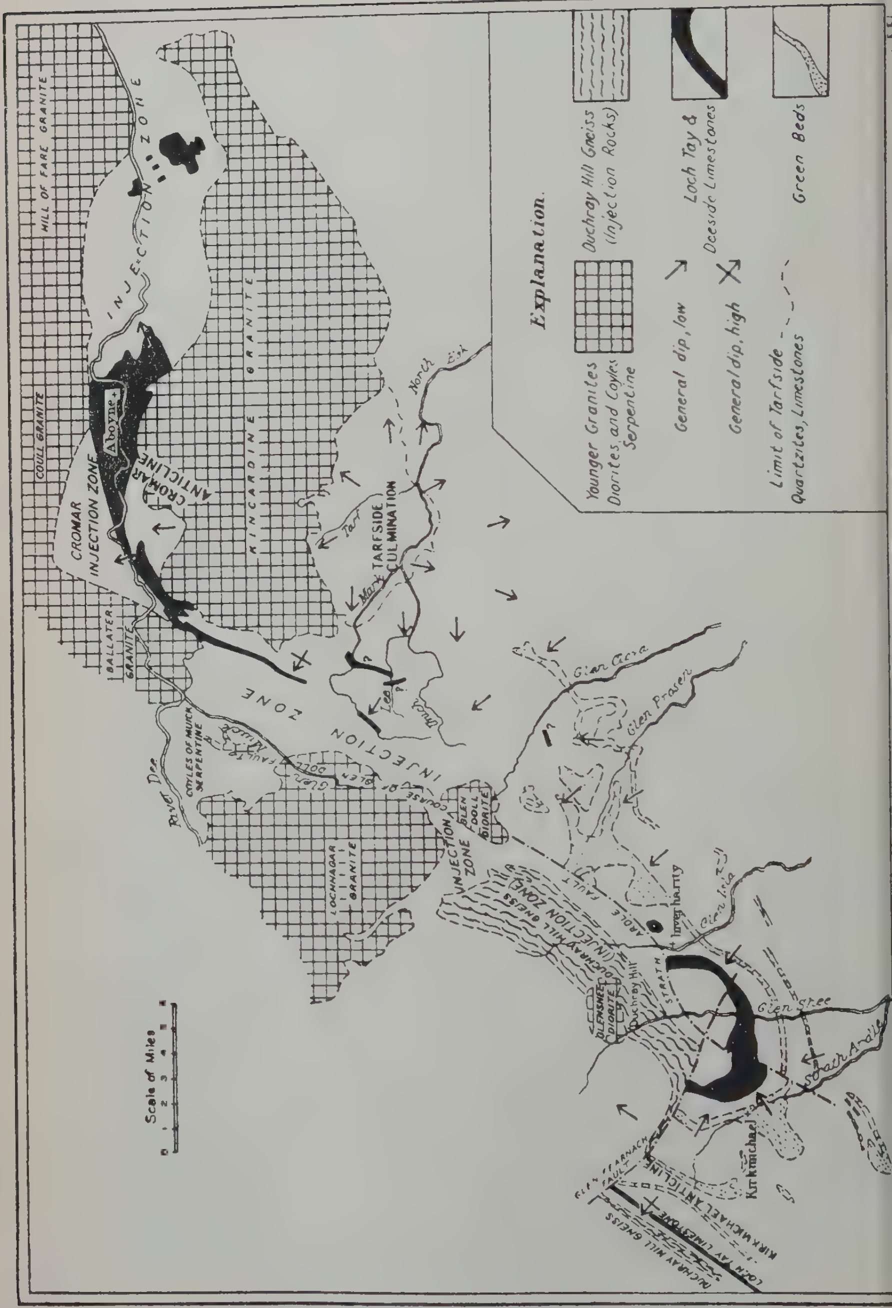
The only remaining paper concerned with the area of the proposed Banff

Nappe itself dealt with the metamorphism and migmatisation in the Ythan Valley in the areas of Sheets 86 and 87 (Read, 1952). In this, I gave a synthesis of incidental information contained in other papers by myself (Read, 1923, 1935), by G. Whittle (1936) and by myself and O. C. Farquhar (Read & Farquhar, 1952), and new observations. The Ythan Valley cuts across the western limb of the Buchan Anticline, or the eastern limb of the Turriff Syncline already mentioned, and the ground mostly falls within that dealt with by Wilson in the Sheet 87 Memoir of 1886. The groups established by Wilson were adopted, named and correlated. Most of the rocks concerned are assigned to the Banff Division and comprise the Macduff Slates (=Wilson's 'clay-slates'), the Fyvie Schists (='knotted and andalusite-schists with pebbly quartzite bands') and the Mormond Hill Quartzite (='quartz-schists and quartzites'). I considered that these members of the Banff Division formed 'a unified series of rocks whose original sedimentary character was gritty with calcareous and pelitic intercalations in the east, and pelitic with gritty intercalations in the west' (Read, 1952, pp. 270–1). The remainder of the rocks of the Ythan Valley are the Ellon Series and its felspathised and migmatised derivatives—the whole group being Wilson's 'gneiss' of the Survey Memoirs 87 and 97. The metamorphism and migmatisation increase in grade from west to east. The Macduff Group on the west is in the slate grade and passes gradually eastwards into the andalusite-cordierite-schist grade of the eastern part of the Fyvie Schists and the Mormond Hill Quartzite; the succeeding Ellon Series is in the cordierite-sillimanite-gneiss grade and is permeated to give the oligoclase-biotite-cordierite-garnet-sillimanite-gneiss of Haddo Type, or migmatised to give garnet-spinel-oligoclase-biotite-cordierite gneiss of Arnage Type, this being often mobilised. I considered that the whole progressive metamorphic series of the Ythan Valley was the result of one plutonic operation, increasing in intensity from west to east, or from above downwards (Read, 1952, pp. 277–8). As was mentioned on an earlier page, the metamorphic front in the Ythan Valley slopes gently north-westwards. It is possible that the permeation and migmatisation are slightly later than the impression of the general metamorphism but nevertheless 'the whole plutonic process is essentially a unified one of regional thermal metamorphism culminating in migmatisation' (Read, *loc. cit.*, p. 278). I called the Ythan Valley style of plutonic activity that of 'Buchan Type' and contrasted it with that—the 'Cromar Type'—operative in the region of Deeside, farther south. It was concluded that the Buchan plutonic operations were later than the small-scale folding of the Banff Division and the Ellon Series. 'If a major tectonic discordance such as a nappe-base separates the Banff and Ellon rocks, then these operations are likewise later than the production of this structure. The Arnage migmatites swamp the boundary between the Banff Division and the Ellon Series' (Read, 1952, p. 278).

The development of knowledge of the area of the proposed Banff Nappe and its immediate surroundings has now been set forth. To complete the picture we have to consider modern work on the Dalradian rocks farther to the south, on Deeside and southwards to the Kirkmichael district (see Plate 1). No disrespect is intended if we do not discuss the Survey work in this southern region; Sir Edward Bailey and I, whose more modern investigations are to be dealt with, have already paid our tributes to the Survey workers and especially to that great Highland geologist, George Barrow. The relevant Survey sheets and explanations (where published) are: Sheet 65, map 1911, memoir 1912; 66, map 1897, no memoir; 67, map 1898 and 1929, no memoir; and portions of Sheet 64, map 1913, memoir 1913; 55, map 1902, memoir 1905; 56, map 1895, no memoir; 57, map 1897, no memoir.

The first of the post-Survey publications on this southern area that has to be considered is my study (Read, 1928) of the Highland Schists of Middle Deeside, on the borders of Sheets 66 and 76. Here I mapped the thick Deeside Limestone, with the Glen Tanner Quartzite and Mica-schist Group structurally below it, and the Queen's Hill Quartzite and Mica-schist Group structurally above it. This last stratigraphical group is the southern extension of the gneisses of the Dee–Don watershed of Sheet 76, already referred to; in Deeside it is found to be migmatised to varying degrees throughout its development (Read, 1927) and, besides, appears to be more favoured by basic sill intrusions, now epidiorite. The Deeside Schists are arranged in a flat belt in Deeside and pass westwards and southwards into a steep belt extending south to the Aberdeenshire–Kincardineshire border, the two belts together forming the Cromar Anticline, which plunges gently northwards. The Deeside Limestone clearly has two sides and, though isoclinal folding is developed in the area, there is nothing of the intense 'concertina folding' invoked by Barrow. Farther down the Dee, at Banchory, thick limestone appears as narrow infolds in migmatitic rocks referable to the Queen's Hill Group. I (Read, 1928, p. 767) interpreted this limestone as being the Deeside Limestone reappearing from below on axes of steep folding. Especially important for the evaluation of any Banff Nappe is my correlation of the Deeside Limestone with the Loch Tay Limestone of the standard Perthshire succession of the Dalradian. This proposal is now examined, the relevant factors being shown in Fig. 2 which is reproduced from my 1928 paper.

*First*, E. B. Bailey contributed to my Deeside paper (Read, 1928, p. 768, fig. 3) a map and explanation of the Tarfside Culmination at the southern margin of the great Kincardine granite. Bailey showed that the Tarfside district was characterised by gentle quaquaversal dips, leading to the emergence of quartzites and impure calcareous beds from beneath a thick mass of more or less pelitic gneiss. 'The Tarfside structure is a gentle dome-


Explanation.
Younger Granites, Diorites, and Coyles Serpentine
Duchray Hill Gneiss (Injection Rocks)
General dip, low
General dip, high
Loch Tay & Deeside Limestones
Limit of Tarfside Quartzites, Limestones
Green Beds
Scale of Miles
0 1 2 3 4 5 6
HILL OF FARE GRANITE
COULL GRANITE
INJECTION ZONE
CROMAR INJECTION ZONE
Aboyne
CROMAR ANTICLINE
KINCARDINE GRANITE
TARFSIDE CULMINATION
North Esk
Tarf
Mark
Lee
Unich
BALLATER GRANITE
INJECTION ZONE
COYLES OF MUICK SERPENTINE
River Dee
Muick
FAULT
Glen Doll
COURSE OF GLEN DOLL
GLEN DOLL DIORITE
LOCHNAGAR GRANITE
INJECTION ZONE
Glen Clova
Glen Prosen
DUCHRAY HILL GNEISS (INJECTION ZONE)
Duchray Hill
GLENSHEE DIORITE
STRATH ARDLE FAULT
Inverharity
Glen Isla
Glen Shee
Strath Ardle
Kirkmichael
GLEN FEARNACH FAULT
KIRKMICHAEL ANTICLINE
LOCH TAY LIMESTONE
DUCHRAY HILL GNEISS

like culmination of pitch affecting a north-easterly trending anticline' (*loc. cit.*, p. 768). Bailey and I agreed with Barrow that the Tarfside rocks pass in a south-westerly direction far below the position of the main outcrop of the Loch Tay Limestone. To the north of the culmination, the Deeside Limestone lies structurally high above the Tarfside rocks. The Deeside Limestone and the Loch Tay Limestone thus agree in structural position with respect to the Tarfside Culmination. *Second*, the horizon west of, or structurally above, the main outcrop of Loch Tay Limestone—this horizon is that known as Ben Lui Schists in the Perthshire succession—is the site of considerable migmatisation, especially well known among the products being the Duchray Hill Gneiss, (Williamson, W. O., 1935). From Duchray Hill this migmatite zone can be followed into Glen Muick and then into Deeside where it lies above the Deeside Limestone. I considered that this migmatite zone everywhere followed a continuous outcrop of Ben Lui Schists; in other words, I correlated the Queen's Hill Group of Deeside with the Ben Lui Schists of Perthshire. *Third*, as already mentioned, this joint horizon above the Loch Tay Limestone of Perthshire and the Deeside Limestone of Aberdeenshire is also a preferential one for the intrusion of basic sills, now epidiorites, older than the migmatisation. I therefore advanced the correlation:

| *Aberdeenshire* | *Perthshire* |
|---|---|
| Queen's Hill Group | Ben Lui Schist |
| Deeside Limestone | Loch Tay Limestone |
| Glen Tanner Group | Pitlochry Schist |

I admitted that the Deeside Limestone cannot be 'walked' into the Loch Tay Limestone, but suggested that this was not to be expected in the poorly exposed ground that comes between their known outcrops. Further, I admitted that the beds associated with the Deeside Limestone are rather more siliceous than the corresponding beds associated with the Loch Tay Limestone, and that the Green Beds, a constant horizon found south-east of the Loch Tay Limestone all across Scotland as far north as Glen Clova, had not yet turned up in Aberdeenshire. These admissions did not shake my faith in the correlation of the Deeside and Loch Tay limestones, nor does their present recital produce any different effect on me. The Loch Tay Limestone is known with complete confidence from Campbeltown in Argyll to Glen Isla in Angus, a thick limestone appears on the same general line of strike and in a similar stratigraphical position farther north. If this Deeside Limestone is not the Loch Tay Limestone, then some tectonics still more remarkable than those I shall propose have to be contemplated.

Finally, I concluded that 'the structure of the Deeside Schists continues the structure of the equivalent horizons in Perthshire. The northward-pitching Kirkmichael anticline is represented, *en échelon*, by the similarly northward-pitching Cromar anticline' (Read, 1928, pp. 771–2). A few years earlier the tectonics of this Perthshire ground had been dealt with by Bailey (1925). Among his results significant for this review are, first, the presentation of the 'Flat Belt' of the Southern Highlands in the Kirkmichael ground, with the beds arranged in the *Tay Order*, with Ben Lui Schist structurally overlying Loch Tay Limestone, and second, the recognition of the East Perthshire Culmination of Pitch, passing north-eastwards along Glen Fearnach, above Kirkmichael. North of this culmination there is 'a north-easterly pitch responsible for swinging the outcrop of the Loch Tay Limestone and overlying zones south-eastwards towards Kirkmichael'; south of the culmination the pitch is south-westerly. In later papers Bailey extended his Perthshire work. Of interest in our present enquiry are the generalised map of the Perthshire culmination (Bailey, 1928, fig. 1, p. 743) and the following statement by Bailey & McCallien (1937, p. 115): 'Throughout (Schichallion to Braemar), the big movements have been towards the south-east, with local twists and adjustments. . . . It is now safe to claim south-eastward movement as overwhelmingly characteristic of the south-east Highlands.'

The Second Edition of the *British Regional Geology: The Grampian Highlands* (1948) summarised the modern views on the Perthshire Dalradian which are of present interest to us. It is accepted (p. 17) that the *stratigraphical* order of the Perthshire Dalradian is: *lowest*, Blair Atholl Series, Central Highland Quartzite, Ben Eagach Black Schists, Ben Lawers Calcareous Schists, Ben Lui Garnetiferous Mica-schists, Loch Tay Limestone, Pitlochry Schists and Aberfoyle Slates, Green Beds, Leny and Ben Ledi Grits. The Loch Tay Inversion is traced from Kintyre to Deeside (p. 32); the *structural Tay Order* in Deeside, already referred to, is therefore the inverted stratigraphical order. The Ben Lui–Kirkmichael flat recumbent fold is a recumbent syncline, indicating a movement of upper layers towards the south-east (p. 32). A diagrammatic section, provided by Bailey, is of great importance in the further exploration of a possible Banff Nappe and is reproduced in simple form in Fig. 3. My final comment is that if the correlation of the Deeside and Loch Tay Limestones is accepted as correct, then from these latest interpretations, it follows that the Deeside Schists are the inverted upper limb of the continuation of the Ben Lui–Kirkmichael recumbent syncline.

This lengthy exposition of the development of knowledge of the Highland Schists of north-east Scotland has been a necessary preliminary for adequate presentation of my proposed Banff Nappe. I have been careful to give abundant page references and many short quotations so that an exposition as impersonal as possible could be available. I believe my occasional comments are honest, or at least as honest as can be expected of

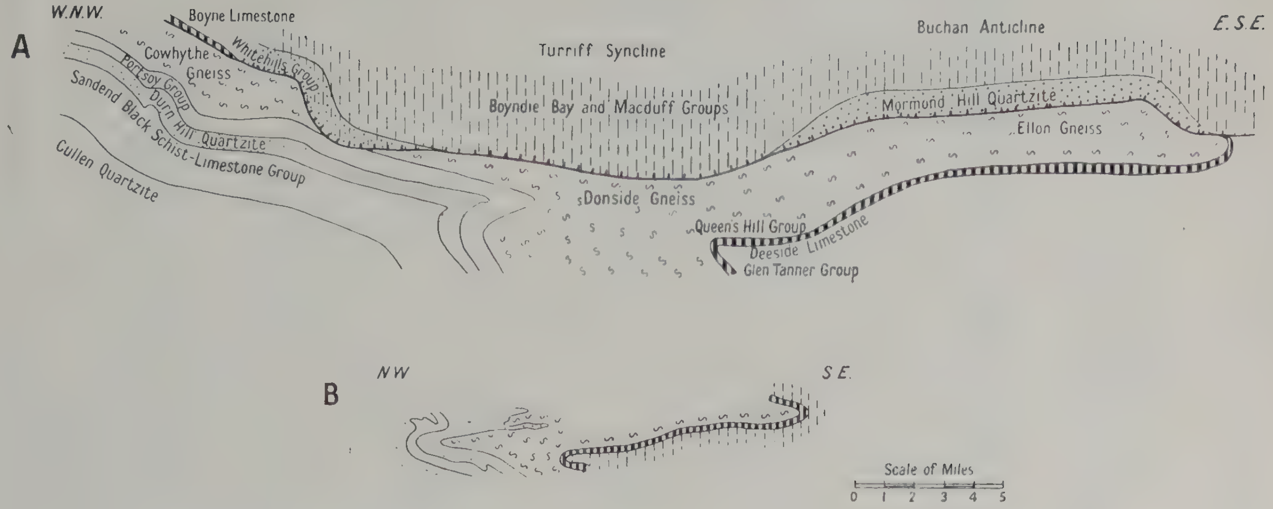


Fig. 3. A: diagrammatic section across the Banff Nappe and diagrammatic section across the Kirkmichael recumbent syncline (see Plate 1)

a Highland geologist. We are now equipped to consider the case for the Banff Nappe.

## 3. THE CASE FOR THE BANFF NAPPE

The interpretation of the schist geology of north-east Scotland that I now develop has been foreshadowed in the previous pages. It is briefly this:

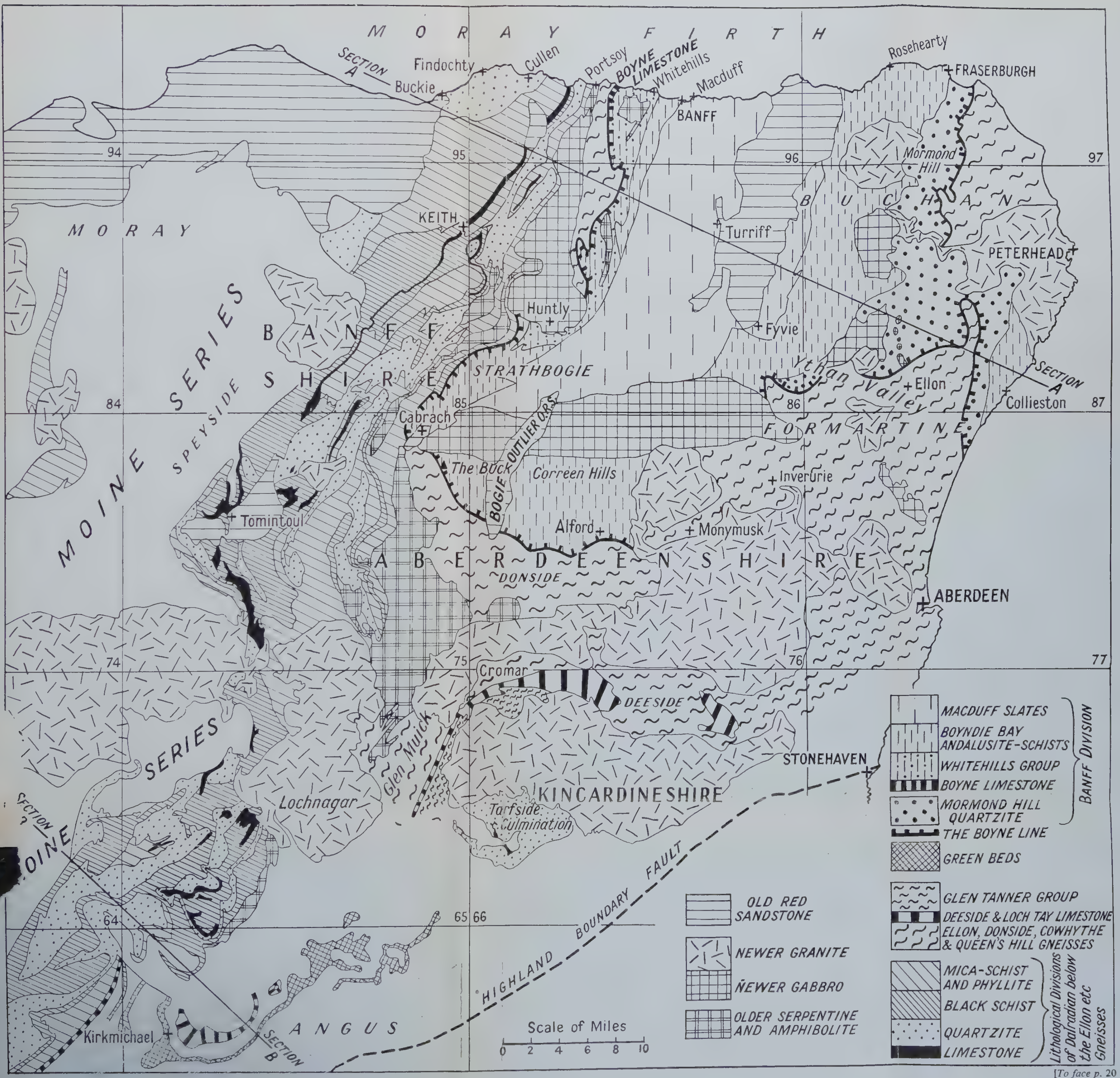
> The rocks of the Banff Division, probably the equivalents of the Upper Dalradian of Perthshire, form a tectonic sheet on the Lower Dalradian, the separation plane cropping out as the Boyne Line. Beneath the Banff Division, the Lower Dalradian is arranged in a recumbent anticline, closing south-eastwards and broken in its upper limb by the Boyne dislocation. The core of the recumbent anticline is made of gneisses, often migmatitic in origin; above these gneisses, in the Banff Division itself, is the wide development of andalusite-cordierite-metamorphism typical of this province. The metamorphic front is gently undulating. The migmatisation and metamorphism are broadly later than the small-scale and large-scale structures, but it may be suggested that the great movement of the gneiss was assisted during some stage of its history by its juicy condition of migmatisation. The so-called Buchan Anticline and Turriff Syncline are structures of a special character, in some ways analogous to the 'secondary' folds of other Dalradian regions; they require further study.

In Fig. 3 there is given a diagrammatic section across the Banff Nappe, along the line shown on Plate 1. The two sections of Fig. 3 are drawn to the same horizontal scale; inspection of this figure and of the area of the Banff Nappe given in Plate 1 shows that this nappe is of no mean size.

Before I present the case for my interpretation, I must emphasise that I make no claim to demonstrate the Banff Nappe. My proposals are put forward as an hypothesis that seems to me to cover the majority of the known facts in the metamorphic geology of north-east Scotland. They provide, I believe, the most plausible explanation of the distribution and characters of the rocks and appear to be repugnant to none of the modern views on Dalradian tectonics.

Contemplation of the distribution of the rock-groups given in Plate 1 reveals the requirement of a break of some kind between the Banff Division on the one hand and the Keith Division on the other. I have wrestled, locally, with this problem in my discussion of the Boyne Line in Lower Banffshire and Strathbogie. That there is a problem is clear from the following considerations.

The standard Perthshire Succession of the Dalradian (Read &MacGregor,


MORAY FIRTH
SECTION A
Findochty
Cullen
Buckie
Portsoy
BOYNE LIMESTONE
Whitehills
Macduff
BANFF
Rosehearty
FRASERBURGH
Mormond Hill
BUCHAN
PETERHEAD
Turriff
Fyvie
Ythan Valley
Ellon
SECTION A
Collieston
FORMARTINE
MORAY
KEITH
Huntly
BANFF SHIRE
STRATHBOGIE
Cabrach
BOGIE OUTLIER O.R.S.
The Buck
Correen Hills
Inverurie
Alford
Monymusk
MOINE SERIES
SPEYSIDE
Tomintoul
ABERDEENSHIRE
DONSIDE
ABERDEEN
Cromar
DEESIDE
Glen Muick
Lochnagar
SERIES
SECTION B
MOINE
STONEHAVEN
KINCARDINESHIRE
Tarfside Culmination
HIGHLAND BOUNDARY FAULT
Kirkmichael
ANGUS
SECTION B
Scale of Miles
0 2 4 6 8 10
94
95
96
97
84
85
86
87
74
75
76
77
64
65
66
OLD RED SANDSTONE
NEWER GRANITE
NEWER GABBRO
OLDER SERPENTINE AND AMPHIBOLITE
MACDUFF SLATES
BOYNDIE BAY ANDALUSITE-SCHISTS
WHITEHILLS GROUP
BOYNE LIMESTONE
MORMOND HILL QUARTZITE
BANFF DIVISION
THE BOYNE LINE
GREEN BEDS
GLEN TANNER GROUP
DEESIDE & LOCH TAY LIMESTONE
ELLON, DONSIDE, COWHYTHE & QUEEN'S HILL GNEISSES
MICA-SCHIST AND PHYLLITE
BLACK SCHIST
QUARTZITE
LIMESTONE
Lithological Divisions of Dalradian below the Ellon etc Gneisses

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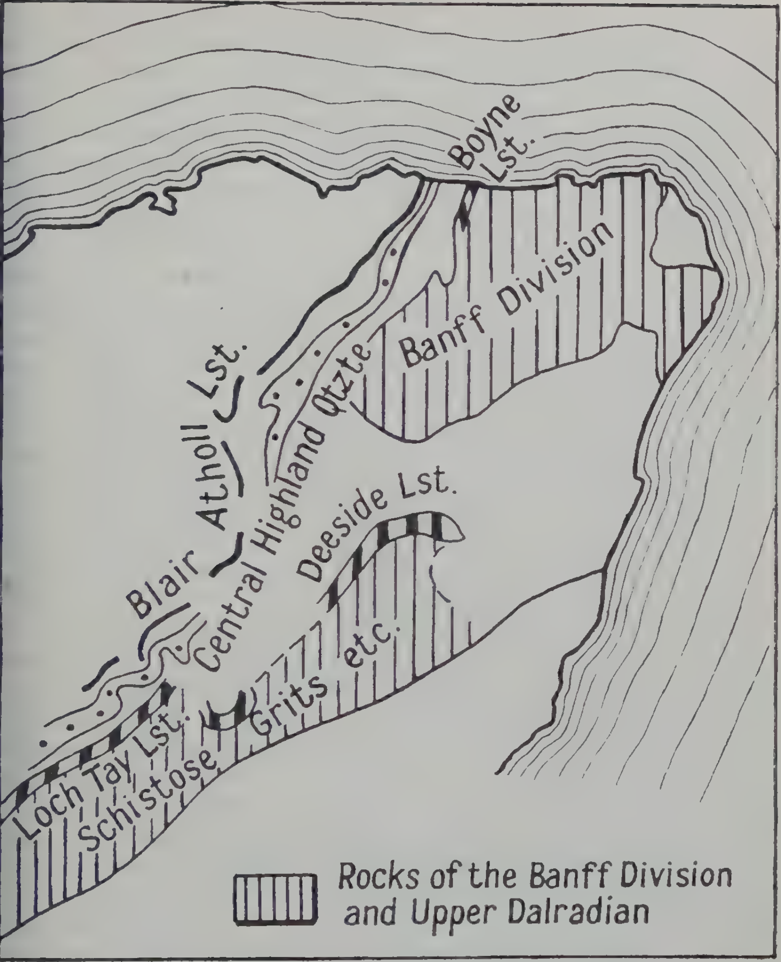

Fig. 4. Elements in the structure of north-east Scotland

1948, p. 17) is perhaps the most securely established fact in Highland geology; at least, this is true for the portions of it that are of interest to the north-east Scottish geologist. It will be recalled that this succession in stratigraphical order, is: Blair Atholl Series, Central Highland Quartzite, Ben Eagach Black Schists, Ben Lawers Calcareous Schists, Ben Lui Garnetiferous Mica-schists, Loch Tay Limestone, Pitlochry Schists and Aberfoyle Slates, Green Beds, Leny and Ben Ledi Grits. The lower portion of this succession, Blair Atholl to Ben Lawers or Ben Lui, extends from regions. As I have stated in an earlier page, my 'great foreign cake of Banff Division rocks'—as I called it in 1923—may yet be of good Scottish make. Accepting this, I correlate the Boyne Limestone with the Loch Tay Limestone, and the Banff Division as a whole with the Upper Dalradian. This correlation has at least the merit of giving a simpler picture of the tectonics of north-east Scotland—and a simpler picture in Highland geology has its advantages.

In my early description (Mem. 86 and 96, 1923, p. 72) of the Banff Division, I commented that a few of the rock-types resembled certain rocks of the Loch Awe Syncline of the south-west Highlands which was then considered by Bailey to form a nappe upon the underlying Iltay Nappe which included the Perthshire Dalradian. I stated that 'certain rather peculiar rock-types of the two areas are similar' but ventured no correlation. Bailey (*in* Read & MacGregor, 1948, p. 23) has more recently correlated the upper part of the Loch Awe succession with the Loch Tay Limestone and succeeding stratigraphical groups of the Upper Dalradian of Perthshire. He now regards the Loch Awe Group as corresponding 'to the unreversed upper limb of the recumbent anticline structurally overlying the Ben Lui–Kirkmichael recumbent syncline' (*loc. cit.*, fig. 7A, p. 32). This position is, of course, strictly analogous to that suggested for the Banff Division in a preceding paragraph though, whilst Bailey has now removed the slide from below his former Loch Awe Nappe, it is necessary to insert a great plane of movement at the base of my Banff Division, because this rests for the most part on equivalents of the Ben Lui Group.

In the previous section of this enquiry, the opinions of various workers on the direction of movement affecting the rocks of the different parts of north-east Scotland were mentioned. For the structures of the Banffshire coast, Elles held that 'powerful impulses from the SE.' were responsible. For north-east Scotland as a whole, Gregory concluded that the main movement came from the east or east-south-east. Over in Speyside, McIntyre argued for a movement 'north-east to south-west in direction, and apparently in general of the upper layers towards the south-west relative to the lower'. Bailey and McCallien for the south-east Highlands claimed a south-eastward movement 'as overwhelmingly characteristic'; a glance at Bailey's Perthshire section given in Fig. 3 shows the Pitlochry–Kirkmichael recumbent syncline closing to the north-west, indicating movement to the south-east. It will be remembered that this syncline can be extended to Deeside. With the aid of sedimentation technique, it may be possible to determine the direction of movement of Banff Division rocks as displayed in the great coast sections of Banffshire and of Fraserburgh and Collieston in Aberdeenshire. Work on these sections is under way by myself, Farquhar, Sutton and Watson and preliminary results indicate a general easterly movement.

In the foregoing paragraphs, I have explored the possibility of a tectonic Banff Division sheet resting on a basement largely made of equivalents of the Ben Lawers–Ben Lui groups of the Perthshire succession. These equivalents are the Ellon Gneisses of Buchan, the Queen's Hill Group of Deeside, the Alford and Donside gneisses and the Cowhythe Gneiss of the Banffshire coast. In Deeside, the inverted Loch Tay (Deeside) Limestone passes beneath these gneisses. As a consequence of these propositions, a situation of great interest arises in the ground south of Aberdeen, and to the south-east of the great Kincardine Granite, up to the Highland Boundary Fault. I (Read, 1928, p. 772) have already made an obscure reference to this situation. The Ellon Gneisses of Buchan and the Queen's Hill Group of Deeside may continue south and east respectively to form the rocks of the coast-section south of Aberdeen, towards the Highland Boundary Fault at Stonehaven. Farther south-west along the fault-zone, the Deeside Limestone should emerge from the Kincardine Granite, but has not yet been shown to do so. It is obvious that the Aberdeen–Stonehaven section, and the ground south and east of the Tarfside Culmination, require investigation. This is being undertaken by the Geology Department of the University of Aberdeen (Williamson, D. H., 1953, p. 361).

The large-scale structural possibilities have been discussed and the small-scale structures in suitable sections are being investigated; there remain the broad flexures exemplified by such structures as the Buchan Anticline and the Turriff Syncline. These structures are comparable, it seems, with the 'secondary' folds, such as the Cowal Anticline, Loch Awe Syncline, Ben Lawers Syncline and others described by Bailey (see Read & MacGregor, 1948, p. 33 and pl. V) in the Dalradian of the south-east and south-west Highlands. The broad flexures in north-east Scotland are clearly not simple folds of a stratigraphical succession; as can be seen from the section of Fig. 3, they may be folds affecting a complex nappe. Their constituents are a matter for immediate investigation.

So far, in these structural discussions, I have not considered the possibility of the Banff Division resting unconformably on its basement, of the Boyne Line being the outcrop of an unconformity and not of a slide or lag. Is the Banff Division a kind of gigantic 'Lennoxian' outlier? This is a question in which the tectonic and metamorphic history of the whole of north-east Scotland is involved. Let us assume for the purposes of discussion that the Banff Division was deposited unconformably on its *present* basement. Certain consequences appear to follow. The major structure of the basement was established before the deposition of the Banff Division cover, but the basement and cover have been affected by a common later folding. As Gregory held for the Dalradian and his Lennoxian, the two have been squeezed together subsequently. Further, it is not unlikely that the basement would have been metamorphosed before the deposition of the unconformable Banff Division, and its rocks should now be polymetamorphic. So far, little has been done in the study of the metamorphic history of the Dalradian rocks anywhere, but the problem of possible polymetamorphism in those parts of the basement immediately adjacent to the Banff Division is made especially difficult by the circumstance that, in this position, it is usually high in metamorphic grade, and extensively migmatised. Recognition of an earlier metamorphism in such rocks would be difficult. I (Read, 1952) have concluded that no metamorphic or migmatitic break exists between the cover and the basement in the Ythan area and so far have recognised no polymetamorphism in the Ellon Gneisses of the basement there. My recent work in the Cabrach, where no gneisses appear in the basement, shows that the Portsoy Group in that region has undergone the same metamorphism as the Boyndie Bay rocks on the other side of the Boyne Line, though of course the resulting assemblages have been controlled by initial compositions. The Portsoy rocks of the basement appear to be monometamorphic.

We have now entered upon the group of problems concerned with metamorphism and migmatisation, and their relation to orogenesis. The metamorphism in north-east Scotland has often been styled abnormal, the standard of normality presumably being that of Barrow's ground in the south-east Highlands. Recently I have argued (Read, 1951) that *sui generis* should be the watchword of the metamorphic geologist, and that the Barrovian zones should not be applied too generously outside their proper original domain. Metamorphic rocks must be permitted to tell their own story even though it differs from Barrow's. As we have seen, the characteristic metamorphic minerals of the Banff Division are andalusite and cordierite. I have shown (Read, 1952), as already summarised, that for the area of the Ythan Valley at least this type of metamorphism cannot be separated from that of the Ellon Gneisses of the basement below the Banff Division, that migmatisation likewise transgresses across the Banff Division boundary and that this combined plutonic act took place after the small-scale folding of the rocks concerned and, of course, after the formation of the Banff Division base, of whatever kind this may be. In the Cabrach, the unified metamorphism is clearly later than the bringing into juxtaposition of the Banff Division rocks and the Portsoy schists of the local basement.

John Horne posed the problem of the regional andalusite-schists of north-east Scotland some seventy years ago; it is time we attempted an answer. With my growing appreciation (Read, 1951) of the significance of migmatisation in regional metamorphism, I suggest that there is some connection between the formation of migmatites round about the Ben Lawers–Ben Lui horizon and the production of andalusite-schists immediately above this horizon, i.e. about the base of the Banff Division.

Once again, the Cabrach area is of interest. I have suggested above that the gneiss group of the basement lies below, and to the east, of the Boyne Line in this region; the andalusite-metamorphism is found above, and to the west, of the inferred position of the gneisses. Thus, though at first sight it seems that the constant association of gneiss, often migmatitic, and andalusite-schists fails in the Cabrach, yet, if my interpretation of the local structure is correct, there is really the closest association. It is reasonable, in my view, to propose that the 'abnormal' andalusite-metamorphism of north-east Scotland occurs in a kind of gigantic regional thermal aureole about a locus of migmatisation; the migmatites form a flat body and the metamorphic front is correspondingly flattish.

It is tempting to go on to suggest that the building-up of the great core of gneisses of the recumbent anticline and its south-easterly under-thrusting below the Banff Division (as shown in Fig. 3), were the consequences of increased mobility resulting from migmatisation. As is obvious, there are difficulties of timing in this suggestion; the metamorphism and migmatisation outlast the movements. But the suggestion can remain for further exploration and discussion.

I have now advanced the hypothesis of the Banff Nappe as a reasonable interpretation of the ground. Whether it will survive, and in what form, remains to be seen. As I have hinted, I am prepared to go to no stake for the faith that is in me and, if an alternative explanation is forthcoming, I shall scrutinise it with, I trust, a fair mind. Finally, I desire to express my gratitude to my fellow-students of Highland tectonics, Gilbert Wilson, O. C. Farquhar, John Sutton and Janet Watson, for pleasant and fruitful discussion on the ground and elsewhere; they are, I must record, in no way committed to the views expressed in this thesis.

## EXPLANATION OF PLATE

Geological Map of north-east Scotland: based on the maps of the Geological Survey, Sir Edward Bailey and the author.

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## DISCUSSION

PROFESSOR R. M. SHACKLETON welcomed this important statement of the structural conclusions reached by Professor Read after many years of work in north-east Scotland. As a student the speaker had been taken to Banffshire by Professor Read and had been intrigued ever since by the tectonic problems there. He thought that the interpretation now suggested followed naturally from the work previously published and led to an elegant explanation of the differences in metamorphism above and below the migmatites; it should stimulate more work in this fascinating area.

Professor Read's interpretation depends to some extent upon the evidence that the succession in the Perthshire flat belt is upside-down. Surprisingly little direct evidence for that inversion has been published (the indirect evidence is very strong); the speaker said that he himself had seen enough inverted graded bedding to be satisfied of the reality of this inversion. Its known extent, from Kintyre to Deeside, nearly two hundred miles, shows that the Tay Nappe (Iltay now seems inappropriate) is a huge structure. The 'Banff Nappe' is the upper limb of this Tay Nappe. A feature which especially impressed the speaker, in the sections of both Professor Read and Sir Edward Bailey, was the immense and rapid increase in amplitude of the recumbent fold at successively higher stratigraphical levels. Professor Read's section also shows a great lag (Boyne Line) in the upper limb, in the rear. These features seemed to the speaker plainly to imply flow under the influence of gravity—south-eastward flow in the south-eastern flank of the Highland welt.

The speaker enquired about the relation of the slaty cleavage in the Banff syncline to schistosity at deeper levels. Is this slaty cleavage related to the nappe-movements, or to later folding?

DR. J. SUTTON said he was grateful for a paper which brought together a summary of the available facts on an intriguing area. He did not regard the concept of the Banff Nappe as a thoroughly satisfying hypothesis. There were difficulties in accepting the supposed outcrop of the Boyne Line on the Banffshire coast as a plane of great movement. He suggested that the change in the nature of the sedimentation which occurred in Middle Dalradian times, when the greywackes of the Upper Dalradian succeeded the well-sorted Lower Dalradian sediments, indicated important Middle Dalradian crustal movements. Was it possible that parts of the Lower Dalradian were being eroded at the time that the Upper Dalradian of Banffshire was being laid down? Such a state of affairs might lead to local unconformities and breaks in the succession, and might explain the odd distribution of rocks near the suggested course of the Boyne Line. He enquired whether the rocks stratigraphically above the Deeside Limestone were lithologically comparable with those overlying the Boyne Limestone.

The suggestion that the andalusite of the Banff Division formed as a result of granitisation proceeding below was an attractive one. On the Banffshire coast, however, it appeared as if the migmatisation in the Cowhythe gneiss was at its height before the final metamorphism of the Banff Division occurred. He hoped to produce the structural evidence for this belief in the near future, in a joint paper with Dr. Watson.

PROFESSOR READ, in reply, was gratified to have Professor Shackleton's general support for the proposal of a Banff Nappe and he was especially glad to know that the Loch Tay inversion was a reality. Professor Shackleton's suggestion of gravity-flow towards the south-east in the higher structural levels was one which the author found increasingly attractive. Detailed work by him and Dr. O. C. Farquhar in the Buchan district, especially on the two great coast-sections of Collieston and Fraserburgh, showed a structural style there that could best be explained by flow off the rising dome of Mormond Hill Quartzite—the doming resulting from the upward movement of the migmatite core of the Banff recumbent sheet. The cleavage in this Buchan area was of axial plane type in small recumbent folds and was reasonably related to the general nappe-movements.

The author regretted that Dr. Sutton did not find the hypothesis of a Banff Nappe completely satisfying. The main argument for this nappe was, of course, the distribution of the rocks; especially that of the Loch Tay–Deeside–Boyne Limestone. Definite dislocation-planes were likely to be unobtrusive, since the metamorphism over most of the area was post-tectonic. Of course it was possible that, during the deposition of the Upper Dalradian or Banff Division, some part of the Lower Dalradian or Keith Division was exposed to denudation. In general, it seemed that rocks of greywacke-facies occurred stratigraphically above the Loch Tay–Deeside–Boyne Limestone, and of orthoquartzite-facies below this horizon—but the author was not able to recall whether this distinction was observable in Deeside itself. The Loch Tay Limestone appeared to be so constant a horizon from Ireland to Aberdeenshire that its disappearance farther north was better accounted for by the Boyne Lag than by unconformity.

It was of course possible—indeed likely—that in certain parts of the Banff Nappe movement and migmatisation-metamorphism were more closely connected than in others. These were matters for detailed study and the author looked forward to the results of the work of Dr. Sutton and Dr. Watson on these questions along the Banffshire Coast-section.

# The Volcanic and associated rocks of Giffard Bay, Jersey, Channel Islands

by MISS M. CASIMIR and F. A. HENSON

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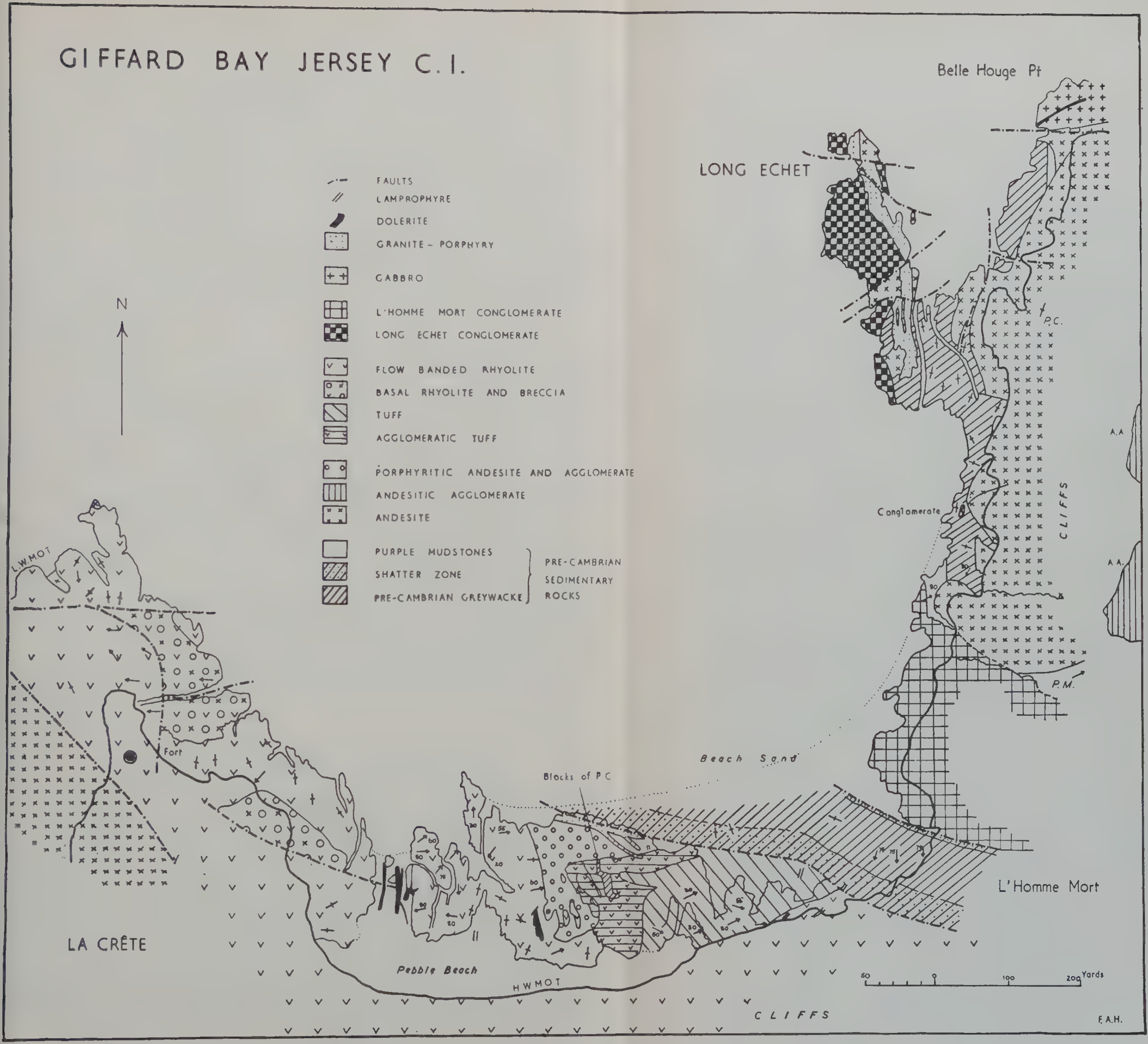
## 1. INTRODUCTION AND HISTORICAL REVIEW

THE AREA NOW described is a small bay on the north coast of Jersey, extending between La Crête Point in the south-west, and the rocky islet of Long Echet in the north-east, half a mile apart. Overlooking Giffard Bay is Les Platons, the highest point on the island. In the bay, which is reached by steep paths at La Crête and Long Echet, is a great variety of sedimentary, volcanic and hypabyssal rocks, exposed at low tide. The area has been mapped in detail; the topographical and preliminary geological mapping was completed before the war (M.C.), and the detailed geological mapping has been finished recently (M.C. and F.A.H.). The laboratory work was carried out in the Department of Geology of the University of Nottingham (F.A.H.).

During the past 150 years numerous papers on the geology of the Channel Islands, and of Jersey in particular, have been written by both British and French authors. They are largely descriptions of the various rocks, particularly the volcanic suites, but little attention has been paid to the


GIFFARD BAY JERSEY C.I.
Belle Houge Pt
LONG ECHET
FAULTS
LAMPROPHYRE
DOLERITE
GRANITE – PORPHYRY
GABBRO
L'HOMME MORT CONGLOMERATE
LONG ECHET CONGLOMERATE
FLOW BANDED RHYOLITE
BASAL RHYOLITE AND BRECCIA
TUFF
AGGLOMERATIC TUFF
PORPHYRITIC ANDESITE AND AGGLOMERATE
ANDESITIC AGGLOMERATE
ANDESITE
PURPLE MUDSTONES
SHATTER ZONE
PRE-CAMBRIAN GREYWACKE
PRE-CAMBRIAN SEDIMENTARY ROCKS
N
P.C.
A.A
A.A.
Conglomerate
CLIFFS
P.M.
L.W.M.O.T.
Fort
Beach Sand
Blocks of P.C.
L'Homme Mort
LA CRÊTE
Pebble Beach
HWMOT
CLIFFS
50 0 100 200 Yards
F.A.H.

[To face p. 30

volcanic rocks at Giffard Bay apart from many references to the pyroclastic rocks which are found there. In 1862 Ansted described some of the volcanics from this area as 'old conglomerate'. Later, De Lapparent, in 1884, referred to Ansted's old conglomerate as 'cette roche que, vu la compacité et la form arrondie de ses partes, a dû être qualifée par M. Ansted d'ancien conglomerat'. He also observed that 'dans les environs du Havre Giffard la pyromeride est brechiforme et prend les allures d'une argololithe'.

In 1886 the Rev. C. Noury published his well-known geological treatise on Jersey. To him must be accorded the distinction of first recognising the main geological structure of the island and of interpreting its history. He described both volcanic and plutonic rocks, as well as the extensive Pre-Cambrian sediments of western Jersey. Noury interpreted Ansted's 'old conglomerate' as tuff.

In 1920 Teilhard de Chardin published a detailed succession of the rocks found in the Giffard Bay area but expressed some doubt about the age and identity of the conglomerates. A year later this was followed by Plymen's paper on the geology of the island. In 1933 Mourant published his paper on the geology of eastern Jersey which contains a full historical review, and a critical examination of the findings of Teilhard de Chardin and Plymen. Mourant simplified the succession at Giffard Bay. One of his maps shows a conglomerate in the andesite series north of the L'Homme Mort faults. This conglomerate contains abundant rhyolite and is obviously younger than the andesites. It is not only on this point that the present authors differ from Mourant, who postulates a throw of 6000 ft. for the L'Homme Mort fault. Such a figure, without any indication of the type of faulting involved, cannot be accepted. Furthermore, the authors can find no evidence of faulting in the reefs at the extreme north of La Crête Point where porphyritic andesite is overlain by later rhyolite. This does not mean, however, that the authors fail to recognise the important tectonic fault from Fremont Point to Vicard.

## 2. STRATIGRAPHICAL SUCCESSION

The sedimentary series, variously described in the past as shales, grits, phyllites and greywacke, are generally accepted as being of Pre-Cambrian age, mainly on account of the complete absence of fossils, and the close similarity of the series with proved Pre-Cambrian rocks in Normandy. There is no real proof of their age, and included volcanics are therefore assumed to be Pre-Cambrian. The geological map of Giffard Bay shows the predominance of Pre-Cambrian sediments and andesite north of the L'Homme Mort fault and rhyolites, mainly of flow-banded type, south of the fault.

(a) **Pre-Cambrian sediments.** The main exposure of the Pre-Cambrian sediments is at L'Homme Mort in the south-east corner of the bay. Its total width varies between fifty and fifty-five yards. Both northern and southern boundaries are faulted, so the mass is a horst structure at this point, with down-faulted newer rocks to north and south. Differential erosion of the Pre-Cambrian, the conglomerates and associated rocks to the north, and the rhyolite to the south, has resulted in a marked topographic feature where the sediments occur. This effect has been emphasised further by gullying along the lines of faulting, and within the fault-breccia.

The sediments at L'Homme Mort are similar to the fine grey-green greywackes which form such a large part of western and central Jersey. Generally bedding and structures are difficult to interpret in this series, but here the rocks are almost vertical, with high dips to the south. The northern boundary, which has a fault-breccia of one foot in width, shows conglomerate faulted against the sediments. The fault-boundary has been traced over seventy-five yards. The southern boundary, where rhyolites are faulted against the sediments, shows a much wider (100-ft.) brecciated zone in the sediments. Clearly this is a major tectonic displacement. The fault is exposed in the cliff, and runs out to sea in a north-westerly direction. Here it is difficult to ascertain the width and continuity of the brecciated zone, but the trend of the fault is clear.

At Long Echet the Pre-Cambrian sediments are well exposed. These rocks, which are mainly vertical, consist of alternating bands of fine grit and mudstone. The coarse grit bands vary from less than an inch to over ten inches in thickness. They are continuous in length over distances of up to thirty yards, but they change considerably in thickness. Differential weathering of the series, which is predominantly grey-green in colour with slightly lighter arenaceous bands, illustrates the rhythmic conditions of sedimentation under which its beds were formed, and accentuates their structures. In this area the sediments are contorted, showing incipient boudinage and drag-structures.

Two large gullies dissect the sediments, separating the islet of Long Echet from the mainland. These indicate the position of minor north–south faults. Such faulting occurs to the east of Long Echet, where the western development of one of the early andesite flows is down-faulted to the west. This resulted in the tongue of sediments now seen between the main flow and the faulted western part.

The most northerly development of the Pre-Cambrian rocks occurs farther north, near Belle Hougue Point. Once again the sediments are almost vertical, but here there is a transition from the normal mudstones and grits to purple mudstones. These last constitute a variation in the normal succession, marking the end of Pre-Cambrian sedimentation in this area. Their purple coloration, and the presence of magnetite dust in them, suggest that they were formed during the first stages of the volcanic period when fine volcanic dust settled through comparatively shallow seas to alter the sediments forming at that time. The purple mudstones are often found in association with the earliest andesitic lavas, and are not found elsewhere in the Pre-Cambrian of Jersey.

(b) **Andesite group.** (i) *Andesite.* The andesites are the oldest volcanic rocks of Jersey. At Giffard Bay they occur both north and south of the major fault-system of L'Homme Mort. The main exposures north of the fault are at Long Echet, Belle Hougue, and in the surrounding cliffs in the area, where the lavas rest unconformably on the Pre-Cambrian rocks. South of the major fault-system at La Crête Point, and in the centre of the bay, andesites are restricted in their development, and their relationship to the Pre-Cambrian sediments is not seen. Petrographically, all the andesites are fine-grained, and fairly uniform in character.

At Long Echet andesite occurs in three disconnected areas, in the northern, central and southern parts of the islet respectively. Here the andesite is similar to that which occurs a hundred yards farther east, at the foot of Belle Hougue. Andesite is in contact with an intrusive granite-porphyry dyke, a younger conglomerate and Pre-Cambrian sediments. In the southern exposure, andesite overlies the Pre-Cambrian sediments. Originally this isolated mass of andesite must have formed part of the larger flows which overlie almost vertical sediments, some fifty yards to the east, although direct evidence of this is lacking. In the latter locality, more extensive and thicker lavas, considerably affected by numerous small faults, overlie both the mudstones and grits of the Pre-Cambrian, and the purple mudstones.

Three distinct lobes of andesite occur in the cliffs south-east of Long Echet; the most southerly of these flows overlies both the blue-grey mudstones and the purple mudstones. Although the present form of the andesite suggests an original lava-flow surface, and may indicate its initial extent, there is little direct evidence to support these views. Large patches of conglomerate, close to these lobes, suggest that these features have existed, as such, from the end of the rhyolite stage. They may well represent slightly modified original structures. The occurrence of altered sediments within the andesite at this locality indicate the irregular and contaminated 'front' of an advancing flow.

All the lava flows in this area have a general inclination of 30° to 40° to the west. This is particularly well-demonstrated by the most southerly exposure of andesite, where the lavas overlie purple mudstones 80 yds. north of L'Homme Mort. Here the base of the lava flow is just above sea-level in the shore-section, but in a small cliff-gully to the east, the base of the same flow is 85 ft. above sea-level.

At La Crête fine-grained andesite, which is similar both macroscopically and microscopically to the andesites at the eastern part of Giffard Bay, forms an extensive reef west of the Fort. It is bounded on the north by down-faulted rhyolites. The fault-plane is inclined northwards at 70° to 80° and shows slickensided surfaces. Little or no brecciation of either andesite or rhyolite occurs along the fault. It is impossible to form an accurate assessment of the throw of this dislocation but since the later porphyritic andesite occurs both at the extreme northern tip of the reef in this area, and sporadically in the cliffs south of the Fort, probably the fault has a maximum throw of about two hundred feet.

(ii) *Andesitic agglomerate*. This rock is associated with the andesite lavas in the upper cliffs east and south-east of Long Echet and varies between two and ten feet in thickness in its various exposures in this area. In an otherwise smooth but steep slope, covered with gorse and bracken, it forms distinct topographical features.

This mottled grey-green and purple rock is formed of angular and partly-rounded fragments of both Pre-Cambrian sediments (including purple mudstones), and andesite, embedded in a very variable fine tuff. The largest pyroclasts vary between 1.0 and 3.0 cm. in length, and many have partly-rounded outlines. As might be expected in a rock of this nature, stratification is poorly developed.

Andesitic agglomerate is generally found above the andesite lavas, but it is also found between the higher flows. Although the succession is inclined at 40° west in this locality, the evidence of abundant andesite within the series, and the complete absence of the later porphyritic andesite, suggests that the andesitic agglomerate is pene-contemporaneous with the last of the fine-grained andesite lavas, and older than the porphyritic andesites. There is no evidence of a volcanic vent in this area.

(iii) *Porphyritic andesite and agglomerate*. These rocks are confined to a relatively small area, north of the pebble beach in the centre of the bay, where they are exposed between basal rhyolite, to the west, and agglomeratic tuff, to the east. The size of the exposure varies with the movement of beach-matter. Nevertheless, over a long period it has been possible to examine the whole surface of the exposure rock. These heterogeneous rocks probably mark the end of the first volcanic phase.

This group, which is predominantly formed of fragments of a porphyritic andesite resembling that of the St. Helier area, fine-grained andesite and tuff, is uncommon in the volcanic series in Jersey. It is characterised by the irregular occurrence of large masses of porphyritic andesite which grade into brecciated, fine-grained andesite and tuff. The intimate mixing of the two andesites—particularly the brecciation of the fine-grained variety and incorporation of tuff—is considered to be the result of a later porphyritic lava moving over the irregular ash-covered surface of an earlier flow. Porphyritic andesite also occurs in the extreme tip of the reefs at La

Crête Point, where it is overlain by rhyolite, and in the cliffs due south of the Fort at the same locality.

(c) **Rhyolite group.** (i) *Agglomeratic tuff.* In the centre of Giffard Bay, due east of the main outcrop of porphyritic andesite and agglomerate, and unconformable upon the last member of the andesite group, occurs the basal member of the rhyolite suite. This rock, dominantly agglomeratic, heralded the onset of the main rhyolite lavas. It is composed of angular andesitic fragments and partially-rounded fragments of andesite, as well as spherulitic rhyolite, embedded in tuff.

Only in the area due east of the porphyritic andesite does this rock form a marked topographical feature. This is mainly due to the presence of massive blocks of Pre-Cambrian sediments at the base of the tuff. The greater part of the beach-outcrop is often covered by shingle and the best exposures occur in the bottom of deep gullies to the east, below the overlying tuffs.

Although predominantly agglomeratic in character, these rocks are varied in their lithology; the lower part of the series is composed of very thin bands of well-bedded pale brown, yellow and purple tuffs interspersed with coarser agglomeratic horizons. In the upper part, the bands of tuff become more numerous and much thicker until eventually the rock contains few agglomeratic bands.

The massive blocks of Pre-Cambrian sediment which occur in the western and lower part of the agglomeratic tuffs are identical with the normal Pre-Cambrian sediments. They show micro-folding and faulting, and are inclined at different angles to each other. This haphazard arrangement, and the distortion of the thin tuffs and agglomerate below them, suggest that they were ejected from a nearby crater, in paroxysmal outbursts, at the beginning of the rhyolite phase.

(ii) *Tuff.* Overlying the agglomeratic tuff, and conformable upon it, are the well-bedded tuffs which extend northwards and eastwards against the L'Homme Mort fault. This series dips 30° to 50° east and is a hundred to a hundred and fifty feet thick. In colour these rocks vary from light grey, pale yellow and blue-grey to purple and occasionally pale green. The most common colours are pale grey-green, and a blue-grey to purple.

The lower part of the series consists of irregular bands and lenses of these two common groups, whilst more massive and lighter-coloured tuff forms the upper part. The lower part of the series is best seen in deep north–south gullies which dissect the exposure. In these gullies the characteristic feature of alternating dark-coloured and light-coloured bands is striking. In thickness the individual bands vary from three to nine inches, the lighter bands being thicker. Frequently the tuffs are lenticular, and are much affected by small-scale faults. In their general appearance the rocks closely resemble the recent ashes of Paricutin, described by Ordõnez. The sizes of the lenses vary, the smallest being less than an inch in length while the largest extends over several yards. A common feature is that all have been distorted by compaction, faulting and, very occasionally, by displacement due to volcanic bombs. These bombs are elliptical in form and are mainly confined to the lower tuffs. Several large fragments of rhyolite occur. These must be interpreted as representatives of early flows which had not reached the Giffard Bay area by the time the tuff was formed.

The upper part of the tuff is less striking, on account of the absence of the dark purple bands. In appearance it is more massive than its lower part. Near to the main southern fault, at L'Homme Mort, the tuff is overlain by flow-banded rhyolite.

(iii) *Basal rhyolite and breccia.* North-east and south-east of the Fort at La Crête, and associated with contorted and faulted flow-banded rhyolites, occur two areas of contaminated rhyolite. These are the basal flows, and they contain abundant inclusions of andesite and Pre-Cambrian sediments. The flow-banded rhyolites in this area also contain varying amounts of andesite and sediment, the former being more abundant. From the faulted andesite-rhyolite junction, west of the Fort, there is a general but slight increase in the degree of contamination towards the north-east.

In the areas shown on the map the basal rhyolites and breccia contain up to 30% derived material. In the area south of the east–west fault-gully, east of the Fort, the amount of derived material is variable. Near to the north–south fault in this locality the inclusions have been elongated by movement of the rhyolite, while 20 yds. to the east large blocks of andesite, some ten inches in length, occur. Here there has been little or no fragmentation of the andesite, and, furthermore, andesite from this flow is much fresher than that at Long Echet. The andesitic inclusions are predominantly of the fine-grained type and have a general north–south elongation, near to the fault. From south to north is assumed to be the direction of movement of the basal rhyolites in this area. This arrangement, with coarse andesite inclusions in the east, and filaments of andesite drawn out near to the fault, suggests that the earliest rhyolites in this area moved over an irregular surface of older andesite and Pre-Cambrian rocks. It is most likely that the earlier flows are those containing coarse andesite inclusions, in which case the 'succession' is from east to west.

North of the second contaminated rhyolite, 100 yds. south-east of the Fort, an unusual green band occurs in rhyolite. This band, rarely exceeding two feet in thickness, is steeply-inclined and has a sinuous north–south trend. It is considered to be an altered tuff incorporated within rhyolite, and marks the base of a rhyolite flow later than the earlier contaminated rhyolite. Irregular filaments of this 'green band' occur south of the main exposure. It is significant that the orientation of this band coincides with the direction of movement, and elongation, of basal flows in the immediate neighbourhood of the Fort.

(iv) *Flow-banded rhyolite*. Flow-banded rhyolites form the cliffs south of L'Homme Mort and occur over large areas of eastern Jersey. In these rocks the flow-banding is exquisite. Occasionally small spherulites are developed, but the greater part of the series are not markedly spherulitic. For the main part these rhyolites, like the basal flows, are inclined steeply. The direction of movement appears to have been towards the north.

Due west of the porphyritic andesite and agglomerate in the centre of the bay the older andesite surface with the rhyolite flows unconformable upon it is seen. The apparent inclusion of rhyolite in the porphyritic andesite is due to the infilling of irregular cavities on the surface of the older flow by the later rhyolite. Some brecciation of the andesite occurred, for the lower surface of the rhyolite frequently contains partly-elongated andesitic fragments.

South of the Pre-Cambrian rocks, at L'Homme Mort, flow-banded rhyolites overlie the tuffs. There is no apparent unconformity, and the tuffs are disrupted by the movement of the flows.

(d) **Conglomerates.** (i) *Long Echet*. Here a conglomerate forms almost the whole of the western part of the island, and also occurs in one restricted locality on its north-east side. In colour the rock is dull grey-green and blue and consists of pebbles of andesite, Pre-Cambrian sediment, and very occasional rhyolite, in a fine matrix. The individual pebbles vary between two and three inches in length, with occasional blocks up to eight inches in length. The matrix is made of very fine fragments of andesite and Pre-Cambrian sediments. Pebbles of rhyolite occur, but are much smaller and very irregular in their distribution.

Although small amounts of rhyolite are present in this conglomerate this does not necessarily mean that the rock itself is younger than the whole of the rhyolites. There is no direct evidence of the age of this conglomerate. It is tentatively proposed that this rock is younger than all the volcanic rocks of the area, but the possibility that it may represent a stage between the end of the andesite phase and the beginning of the rhyolites must not be overlooked.

(ii) *L'Homme Mort*. North of the fault at L'Homme Mort, and faulted against the Pre-Cambrian rocks, is a conglomerate which differs appreciably from the Long Echet conglomerate. It contains relatively abundant rhyolite pebbles, and forms a distinct topographical feature north of the fault. This conglomerate lies unconformably upon the purple mudstones. There are three other small patches of this conglomerate in the area; two are isolated occurrences which rest upon the Pre-Cambrian sediments, while the third is in a gully below the cliff-path at Long Echet. In the latter locality a large boulder of flow-banded rhyolite occurs.

Considerable controversy has characterised earlier discussions about the age of this rock which superficially resembles the Permian Rozel Conglomerate. Pre-Cambrian sediments predominate in the latter but at Giffard Bay the andesites are dominant. The Fremont-Rozel fault, as described by Mourant, is approximately coincident with the Armorican fault-systems of Coutance which throw Lower Carboniferous limestones against Pre-Cambrian. Since the L'Homme Mort Conglomerate is affected by this fault, and the outlier of Rozel Conglomerate at Vicard is not, the Giffard Bay conglomerate must be older than both the Rozel Conglomerate and the faulting.

(e) **Hypabyssal rocks.** (i) *Granite-porphyry*. These minor intrusions, which closely resemble the rhyolites, cut the volcanic series and 'older' plutons in the eastern area of Jersey. In Giffard Bay two granite-porphyry dykes occur; one at Long Echet and the other in the centre of the bay adjacent to the faulted Pre-Cambrian succession.

At Long Echet, the dyke of north–south orientation is affected by small-scale east–west faults which have resulted in small lateral displacements of this intrusion. At the extreme north the lighter-coloured granite-porphyry contrasts strongly with the dark grey-green and blue conglomerate, and is intrusive between this older rock and the andesite. The dyke increases in width in the central part of the island, and it is only on the western side that the contact with the conglomerate is seen. South of this the porphyry intrudes first andesite, and then the Pre-Cambrian rocks. Here it contains large blocks of the sediments, and finally tongues into them.

By contrast, the granite-porphyry in the central bay is poorly-exposed. In direction it is quite different from that of the Long Echet dyke, while in thickness the dyke exceeds 4 ft. in the western exposure, and thins eastwards. The intrusion forks, changes its direction, and fingers-out, after traversing the agglomeratic tuff. The rock is intrusive between the porphyritic andesite and the brecciated Pre-Cambrian succession, and therefore post-dates the faulting. Consequently it is post-Lower Carboniferous in age. The granite-porphyry of Long Echet is affected by the east–west faulting and is assumed to be slightly older than this dyke. The direction of the younger granite-porphyry is partly controlled by the major fault.

(ii) *Dolerite dykes*. In common with all other areas in Jersey, dolerite dykes of slightly different ages occur. The east–west dykes are older than the north–south dykes. In width the dykes vary from 1 to 2 ft. although one dyke 4 ft. wide occurs at Giffard Bay.

The north–south dolerite traversing rhyolite to the west of the Porphyritic andesite and tuff, splits in a southerly direction into lobes which, as Mourant points out, indicates the difficulty with which this dyke penetrates the massive rhyolite. The dyke is exposed over a distance of 20 yds., and thins out to the north.

On the north-east shore are members of the earlier east–west dyke-swarm, and dolerites which cut both andesite and the Pre-Cambrian rocks occur. At Belle Hougue Point a dolerite, 4 ft. in width, cuts the gabbro in a west-north-west direction.

(iii) *Lamprophyres.* Like the younger dolerites dykes of this composition traverse all the main rock-groups of Jersey, and have a general north–south orientation. In Giffard Bay one well-developed lamprophyre dyke, 6 ft. in width, cuts dolerite, thereby indicating a later age than the latter.

Two minor lamprophyres, only a few inches in width, have been found in the shattered and brecciated Pre-Cambrian rocks at L'Homme Mort. They show only slight lateral displacement. Since the main faulting, here, is post-Lower Carboniferous, the lamprophyres are thought to be late Carboniferous or early Permian in age mainly on account of their similarity with proved Permian lamprophyres at Kersanton in Brittany.

## 3. PETROGRAPHY OF THE MAIN ROCK GROUPS

**Pre-Cambrian sediments.** This group is composed of mudstones, siltstones and grits identical with those developed extensively in the western half of the island. The mudstones and siltstones vary in colour from deep rusty brown to brownish-yellow on weathered surfaces, although when fresh the series is characteristically blue-green. Apart from colour-variation, the series is fairly uniform in character and very fine-grained.

In Giffard Bay three local variations occur within the series, viz: the contorted mudstones and grits of Long Echet, the upper members of the series which have been named the Purple Mudstones, and the restricted development of phyllites in the fault-zone at L'Homme Mort. The grits at Long Echet are easily distinguished, macroscopically, on account of their coarser grain-size and their lighter grey-green colour. They also show micro-veining by quartz. The Purple Mudstones are distinguished from the normal series by their deep purple colour, and, to a lesser degree, by well-developed bedding-planes.

Microscopically, the mudstones and siltstones show little trace of bedding. They consist mainly of angular quartz grains (average diameter 0.01 mm.) and sericite, with subordinate chlorite, haematite, magnetite and occasional apatite and zircon. A few of the extremely small quartz grains have partly-rounded outlines, but most of them are very angular, contain few inclusions and exhibit normal extinction. Generally the sericite flakes are slightly larger, show a tendency to sub-parallel arrangement, and are associated with argillaceous matter.

By contrast, the banded Purple Mudstones are striking. The bands vary between 0.5 and 2.0 mm. in width and reveal the characteristic delicate micro-faulting of these rocks. These bands are formed of abundant fine magnetite dust, layered between coarser grains of magnetite and quartz. The lower margins of the bands are frequently diffuse, while there is a general decrease in grain-size of all constituents towards the clear-cut upper margin, thus suggesting graded bedding. The iron ores are angular, with the exception of a few perfect euhedral magnetite crystals.

The essential minerals present in the Purple Mudstones are quartz, sericite, magnetite, haematite and an extremely fine-grained groundmass of sericite, magnetite dust and clay minerals. Throughout quartz is sub-angular to angular, and is rarely more than 0.05 mm. in diameter and generally of the order of 0.01 mm. Felspar is not present, and the common sericite is even finer-grained than the quartz. The iron ores, much commoner than in the lower mudstones and siltstones, form between 5% and 8% of the Purple Mudstones, and in some bands reach 35%. The Purple Mudstones, and the earlier Pre-Cambrian rocks, are clearly members of the greywacke suite.

**Andesites.** (i) *Fine-grained andesite.* Macroscopically, the lavas of the lower group, found mainly in the Long Echet area, are much-weathered pale brown and green rocks of fairly uniform character. When the rocks are fresh (as inclusions in the later rhyolites) small felspar laths, rarely exceeding 1.5 mm. in length, are easily distinguished in a compact blue-grey rock. In some cases, small amygdales are present; in others, hair-like veins of secondary calcite penetrate the rock.

Microscopically, these andesites show considerable variation in mineralogy, texture and grain-size. The most important mineralogical variations are, firstly, the amount of iron ores present, and secondly, the occurrence of pseudomorphs after pyroxene. The commonest andesite is characterised by a blackish groundmass of plagioclase microlites, altered ferromagnesian minerals and iron ores. At a few localities this type shows a sub-parallel arrangement of the felspars. Less frequent is a coarser-grained variant in which iron ores are more abundant, and in which pseudomorphs after pyroxene are quite common. These coarser-grained andesites are generally much altered, the felspars being highly sericitised and the ferromagnesian minerals altered to chlorite and calcite. The latter are either scattered throughout the rock or confined to distinct veins.

Amygdales filled with chlorite occur mainly in this coarser-grained andesite. Very occasionally some relicts of a fine-grained quartz-rich sediment (assumed to have been derived from the Pre-Cambrian rocks previously described) are preserved as xenoliths in the lower andesites above the sedimentary series.

Invariably the plagioclase felspar present is almost completely altered to sericite, with subordinate chlorite, calcite and, rarely, quartz as alteration products. Although the felspars are too small and altered to allow of accurate determination, their low extinction-angles show they are near oligoclase-andesine in composition.

Ferromagnesian minerals are thoroughly decomposed to chlorite, with varying amounts of calcite and antigorite, very occasionally quartz, and more rarely epidote. Diffuse patches of these minerals mark the locations of original ferromagnesians minerals, and frequently show the original external form and cleavages of pyroxene. Often cleavages are indicated by lines of magnetite, and the pseudomorphs are outlined by dark, iron-stained borders. Small fragments of unaltered hornblende occur in one of the higher members of the fine-grained andesites. The other minerals in these fine-grained andesites include talc, epidote, apatite and clinozoisite.

(ii) *Porphyritic andesite.* Macroscopically the blue-grey porphyritic andesite is distinguished from the fine-grained andesites by the presence of comparatively large felspar phenocrysts of felspar (0.25 to 1.25 cm. in length).

Microscopically, these andesites are less weathered and altered than the fine-grained varieties described above. The felspars ($\alpha = 1.541$; X'/001, 11°–14°; biaxial positive) correspond to albite-oligoclase in composition, with 85% to 90% Ab, and vary considerably in size and shape. The greater number are sub-hedral and partially altered to sericite. In addition, all felspar phenocrysts are very much fractured and show alteration to sericite along cleavages and fracture-surfaces. The large felspars also contain abundant euhedral and sub-hedral magnetite, patches of chlorite and, occasionally, are veined with magnetite and ilmenite. The felspars of the groundmass show slightly lower extinction angles (X'/001, 8°–12°), and appear to be mainly oligoclase. Like the felspars of the fine-grained andesite, these microlithic felspars rarely show albite twinning, are much altered and are occasionally swallow-tailed.

The amount of ferromagnesian minerals present in the porphyritic variety is less than in the fine-grained andesites. In both the fine-grained and porphyritic andesites all the ferromagnesian minerals have been chloritised. Aggregates of minute chlorite flakes (colourless and pale green varieties), sericite, magnetite, small crystals of quartz and occasional euhedral apatites are scattered throughout the groundmass. In these patches apatite is variable in size and amount, some crystals attaining 1.5 mm. in length. Pseudomorphs after hornblende and augite are not common, but where they do occur the outline is bordered by magnetite and ilmenite. The cleavages are not preserved.

The amygdales occur sporadically, and vary from 0.2 to 0.4 cm. in length. Often they are elongated, with indistinct margins. The minerals within the amygdales are colourless fan-shaped chlorite, a pale green scaly chlorite, magnetite (up to 1.5 mm. in length), apatite and quartz.

In addition to the felspar microliths and abundant magnetite, the groundmass contains a larger proportion of minute sericite flakes, small diffuse patches of chlorite, and occasional apatite crystals. Apatite, as indicated above, is associated more frequently with the larger amygdales.

**Rhyolites.** (i) *Basal rhyolites and breccia.* Macroscopically, the basal rhyolites and brecciated rhyolite vary in colour, texture and composition. This is due, almost entirely, to the amount of andesite present, and the degree of its fragmentation. The andesite, which is mainly the fine-grained variety, varies in size from large fragments, over 15 cm. in length, to minute fragments of 1–2 mm. in length. The bulk of the contaminating andesite varies between 0.2 cm. and 2.0 cm. in length.

In the coarsest breccias, angular andesite and auto-brecciated rhyolite give rise to a mottled grey-blue rock in which the andesitic fragments vary between 1.0 cm. and 2.0 cm. in length, and form 40% of the rock. In finer-textured rhyolites, where andesite may vary from 20% to 30% of the rock, the fragments vary between 0.25 cm. and 0.75 cm. in length. The most common rock-type, however, is one in which the amount of andesite varies between 5% and 10% of the rock, and the fragments are from 2.0–5.0 mm. in length. In such rocks the flow-banding of the rhyolite is clear, and many of the andesitic fragments show a common orientation which indicates the direction of movement.

The andesite of the inclusions in the basal rhyolite and breccias is much fresher than that of the main andesite flows. Both the fine-grained and porphyritic varieties of andesite are present, the latter being subordinate in amount. In nearly all cases the andesitic fragments in the coarser-grained rhyolites show clear-cut outlines. No apparent alteration has taken place, apart from the abundance of minute grains of magnetite and ilmenite, at the margins of the fragments. The rhyolite in contact with such fragments is finer-grained or glassy in texture.

In some cases, mainly in the finer rocks, the andesitic fragments show interesting examples of veining, brecciation and streaking-out, due to movement of the acidic lava. The early stages are marked by penetration and brecciation of the andesite by extremely fine veinlets of quartz, associated with chlorite and sericite. At times these veinlets follow cleavage directions in the felspars, and occasionally widen to 1.5 mm. Larger veins, traversing felspar phenocrysts of the rhyolite and the andesite alike, are composed almost entirely of quartz commonly accompanied by epidote and rarely zoisite. Diffuse patches of magnetite and chlorite in the flow-banded rhyolite may indicate the remnants of andesite in the enclosing rock.

In some sections, from the lower part of the series, the amount of andesite may vary from 20% to 40%, as already noted. In such rocks the texture closely resembles that of a pyroclastic rock in which fragments of rhyolite, clearly exhibiting flow structure, occur in a matrix of andesite and rhyolite. Scattered magnetite grains are very common in this rock. The absence of any suggestion of bedding, although volcanic dust is undoubtedly present, indicates that these first rhyolite flows picked up fragments from the earlier rocks over which they flowed.

Occasional fragments of Pre-Cambrian rocks occur, but do not exhibit the brecciation, and other structures, noted above; their comparative rarity may indicate that, by this time, there were few exposed Pre-Cambrian rocks in this area.

(ii) *Flow-banded rhyolite*. On weathered surfaces, this rock shows as an alternating series of light and dark bands. The first type of the latter varies between 0.1 cm. and 0.3 cm.; the second type between 0.2 mm. and 0.5 mm. and shows perfect flow-, micro-fold- and fault-structures. On fresh surfaces the rock is almost uniformly dark grey in colour, with faint tinges of deep red and purple.

Microscopically, the flow-banding is shown by the sub-parallel arrangement of alternating thin and slightly thicker bands of minute crystals of quartz and felspar. Often the margins of these bands are slightly glassy. Frequently, the larger quartz crystals are arranged with their *c*-axes parallel to the banding. Generally, however, quartz in the groundmass is present as a micro-crystalline mosaic, with some altered felspar. Micro-spherulitic textures are also developed, and spherulites are frequently elongated in the direction of flow.

Phenocrysts of quartz and felspar are quite common in the flow-banded rhyolites. Quartz is the more abundant, occurring both as euhedral crystals with excellent crystal-outlines, and also in sub-hedral form, with embayed, or partly-rounded outlines. Both types have inclusions, sericite being very common, both as inclusions in the crystals, and in the enclosed groundmass. Both $\alpha$-quartz, commonly with inclusions, and $\beta$-quartz, with few inclusions, occur, the latter forming hexagonal bipyramids.

Phenocrysts of both orthoclase and microcline are present. They show sub-hedral outlines, and occasional development of Carlsbad twins. In most cases these felspars are partially altered to sericite. Only rarely does the quartz or felspar exceed 2.0 mm. in length.

(iii) *Agglomeratic tuff*. Macroscopically, these rocks vary in grain-size from the coarser basal members to the fine-grained upper parts of the series. In addition to the marked angularity of nearly all the fragments, a few partly-rounded fragments occur. Andesites and sedimentary rocks predominate in the lower part, while in the upper part these give way to rhyolite. The tuffs show a corresponding variation in colour, being darker in the lower part, where the sediments are most abundant.

The coarser rock fragments are variable in size, the largest exceeding 3–4 cm. in length, but the bulk of the rock (40% to 70%) consists of angular fragments between 0.2 and 1.0 cm.

Microscopically, the structure of the series and its heterogenity are more striking than they are in the hand specimen. Fragments of andesite, mudstones and rhyolite, and fragments of crystals of quartz, felspar and magnetite, are seen set in a very fine mosaic of quartz and sericite. In ordinary light, glass shards, lapilli and pumice may be distinguished, which are now devitrified and indistinguishable between crossed nicols. Magnetite dust is scattered throughout.

The andesite fragments present are of the fine-grained variety, similar to that at Long Echet, and are remarkably fresh. A few pieces of pyroxene-andesite occur, but are poorly preserved. In fragments of Pre-Cambrian sediments, bedding-planes and weak banding can be seen. Their mineral compositions and textures are identical with those of the Pre-Cambrian rocks already described. Fragments of rhyolite, which are uncommon, may be distinguished by their banding and fine grain. Of the crystal-fragments, quartz is the commonest constituent and occurs as sub-hedral crystals enclosing abundant magnetite dust, and frequently exhibiting large cracks and undulose extinction. The felspars, which are very irregular in outline, are mainly microcline and plagioclase. Orthoclase is not found. Plagioclase, although uncommon, possesses good lamellar twinning and shows only slight alteration to sericite and kaolinite. The extinction angles of these felspars (X'/001, 9°–12°) suggest affinity with the rhyolite rather than with the andesites. Some may have been derived from fragmented andesite, however. Magnetite (often in perfect euhedral crystals), haematite and epidote, are common.

(iv) *Tuff.* In contrast with the underlying agglomeratic tuff, described above, these tuffs are very well-bedded. The series consists of contrasting grey-blue, pale purple and grey-green bands, generally varying in width from 1.0 cm. to 3.0 cm., but occasionally attaining to 8 cm. or 10 cm. in thickness. Often the bands are discontinuous—particularly the lighter-coloured ones—and give rise to lens-structures within the rock. In addition, micro-faulting, often traceable over 5 cm. to 8 cm., but involving only small displacements of 0.2 cm. to 1.0 cm., is common. Scattered throughout are well-defined bands with angular rhyolitic fragments, usually varying between 0.1 cm. and 0.75 cm. in diameter but occasionally exceeding 1.0 cm. All the fragments are orientated parallel to the banding.

Microscopically, the banding of the tuffs shows many interesting features, particularly when examined in ordinary light. The bands show perfect grading, the upper part of each being marked by abundant magnetite dust, often seen as a continuous fine black zone across the section. From the upper part of the band downwards there is a gradual decrease in the amount of magnetite dust and accompanying shards of glass, comminuted glass and pumice. These give way to rhyolite fragments with subordinate glass and magnetite. The thickness of the dark bands varies from 0.4 cm. to 0.6 cm.

In the lighter-coloured bands the groundmass is formed of extremely fine-grained magnetite dust, abundant glass shards, rhyolitic fragments and a low percentage of chloritic matter. Occasionally a few small crystals of quartz and orthoclase occur. The whole series can be described as predominantly rhyolitic vitric tuffs, with subordinate horizons of lithic tuff. Since all the rocks have been devitrified, the textures and structure can be seen only in ordinary light.

## 4. TECTONICS

All the rocks at Giffard Bay have been affected by earth-movements. For the most part, the Pre-Cambrian rocks are vertical, while the volcanic groups are steeply inclined and intensely faulted. Even the youngest group, the mica-lamprophyres, are faulted. These effects are to be expected in an area which was the centre of prolonged vulcanicity in Pre-Cambrian times, and was the centre of an orogenic belt in the later Carboniferous period.

The earliest indications of the coming volcanic stages are found in the Pre-Cambrian rocks, where the youngest members of the series show marked lithological variation at Long Echet before the Purple Mudstones, impregnated with volcanic dust, end the Pre-Cambrian succession. In the period between the earliest andesites and the mudstones, considerable earth-movement took place because these lavas are unconformable upon the Pre-Cambrian rocks. Conditions throughout the volcanic stage were far from tranquil, since violent explosions disrupted earlier lava-flows and sediments alike.

As Mourant has pointed out, the complex major and minor faulting took place in late Carboniferous times. At Giffard Bay the majority of faults are small-scale normal faults, with displacements rarely exceeding a hundred feet and a general WNW. to ENE. trend. Similar small-scale faulting is seen in the Long Echet area. Tear-faulting is quite common.

At L'Homme Mort two large faults divide the area into distinct parts, composed of Pre-Cambrian sediments with andesites in the north, and predominantly rhyolites in the south. In the central bay area, south of the major faults, the top of the andesites and the base of the rhyolites occur within a few hundred feet of each other both on the north and south of these faults. The elongated Pre-Cambrian structure remaining in the fault-zone is a horst. The aggregate throw of the whole fault is given by Mourant as 6000 ft.

This figure cannot be accepted, for several reasons. First, the mylonised zone in the Pre-Cambrian rocks indicates a considerable horizontal component, and suggests large-scale lateral movement. Furthermore, since basal rhyolites and andesites, both porphyritic and fine-grained, occur to the south of the fault, the vertical throw must be limited to approximately the thickness of the andesites, i.e. 2000 ft. (Mourant). Finally, there is some evidence that flow-banded rhyolite overlies the andesites both inland, and to the north of the faults. The obvious fact that the faults constitute a major tectonic zone is not disputed, but the magnitude previously suggested is thought to be far too large.

## 5. CONCLUSION

At Giffard Bay the volcanic and associated rocks reveal the history of some of the oldest volcanic rocks known. In the main, the sedimentary rocks, occurring over a wide area in western Jersey, are of the greywacke suite, and form a monotonous series of folded and faulted mudstones, siltstones and occasional grits. At Long Echet, the sediments show changes in lithology and structure which are here interpreted as changes in the conditions of sedimentation brought about by earth-movements and culminating, later, in prolonged and extensive volcanicity. In the uppermost part of the Pre-Cambrian succession (Purple Mudstones stage), fine volcanic dust appears to have settled through comparatively shallow water to appreciably alter the colour and character of the deposits. The rocks thus formed exhibit graded bedding, with bands of magnetite dust recording the earliest volcanic activity before the arrival of the first and more basic members of the andesite group.

By the time the first andesites were extruded, considerable earth-movement had taken place in the area, for the flows are unconformable on distorted and disturbed sediments. The disruption of the sediments may be a local feature, due to the proximity of a volcanic vent or fissure. The andesitic agglomerate also supports this supposition. Indeed, in some areas the andesites are considered to be conformable upon the Pre-Cambrian rocks. Since pillow-structures are not found, presumably the andesites flowed over the newly-emerged sediments. The andesites are fairly uniform in character and of considerable thickness, although the lowest members are more basic than the upper fine-grained variety and the final porphyritic type. Their arrangement on the cliffs in the eastern part of Giffard Bay suggests that extensive lava-extrusion, in the form of flows, was interrupted by periods when pyroclastic rocks accumulated. The time which elapsed between the end of the first phase of Pre-Cambrian volcanic activity, and the beginning of the second phase, is unknown.

The rhyolitic phase began with violent explosions which fragmented the Pre-Cambrian sediments, and the earlier andesites, and gave rise to the accumulation of considerable amounts of agglomeratic tuff upon the older andesite flows. These earlier agglomeratic tuffs, in which large blocks of Pre-Cambrian sediments occur, give way to much finer tuffs which show graded bedding, and occasional volcanic bombs. Later tuffs, which are over a hundred feet in thickness, record the rhythmic pulsation of the nearby volcanoes during this period and suggest that the first flows of rhyolite did not reach the area until much ash had accumulated. On arrival, some of the earliest flows which appear to have come from the south-east, moved over the surfaces of the older andesites and incorporated large amounts of the latter. Subsequent flows, which passed over the earlier contaminated and auto-brecciated flows, show perfect flow-banding and are comparatively free from andesite.

After the extrusion of the rhyolites, a period of weathering and erosion of the volcanic rocks occurred, as indicated by the conglomeratic deposits of Long Echet and L'Homme Mort. These rocks contain representatives of all the volcanics, and while it is impossible to date them, it is quite likely that they represent the end of the Pre-Cambrian sedimentation.

In Carboniferous times, the area was affected by further earth-movement, and fresh igneous activity took place. Granite-porphyries, and dykes of dolerite and lamprophyres, were intruded. One of the porphyries follows the direction of proved late Carboniferous faulting, while the other, at Long Echet, is affected by the tectonics and is therefore earlier. Mica-lamprophyres cut all the rocks of the area and are possibly Permian in age. The succession, and probable age-relationships, are given below:

| | | |
|---|---|---|
| PERMIAN | Hypabyssal Rocks | 14. Mica-Lamprophyres. |
| EARLY PERMIAN OR LATE CARBONIFEROUS | | 13. Dolerite dykes. |
| | | 12. Granite porphyries. |
| | Conglomerates | 11. L'Homme Mort Conglomerate. |
| (age uncertain) | | 10. Long Echet Conglomerate. |
| | Rhyolite Group | 9. Flow-banded Rhyolite. |
| | | 8. Basal rhyolite and breccia. |
| | | 7. Tuff. |
| | | 6. Agglomeratic tuff. |
| | | 5. Porphyritic andesite and agglomerate. |
| PRE-CAMBRIAN | Andesite Group | 4. Andesitic agglomerate. |
| | | 3. Fine-grained andesite. |
| | | 2. Purple Mudstones. |
| | Greywacke Suite | 1. Mudstones, Siltstones, Grits. |

## ACKNOWLEDGMENTS

The authors wish to express their gratitude to Prof. Percival Allen for helpful advice and criticism in the preparation of the paper; to Prof.

W. D. Evans the authors are also very much indebted for all laboratory facilities and encouragement of their research in Jersey.

## EXPLANATION OF PLATE

(a) Fine-grained andesite from the mainland east of Long Echet. This andesite is thoroughly chloritised, and is traversed by secondary veins of calcite. Chlorite pseudomorphs after pyroxene are abundant. Ordinary Light. x 7.
(b) Fine-grained andesite, showing chlorite pseudomorph after pyroxene. The outer rim of the pseudomorphs are very dark red, due to iron staining; the chlorite is predominantly antigorite. Ordinary Light. x 27.
(c) Basal Rhyolite and Breccia. Fine-grained and porphyritic andesite are intimately mixed in a groundmass of earliest rhyolite. These early flows contain comparatively large quartz crystals. Ordinary Light. x 5.
(d) Flow-banded rhyolite, showing elongated spherulites. Ordinary Light. x 7.
(e) Spherulitic texture developed in main rhyolite lava. Ordinary Light. x 16.
(f) Tuff. This rock contains abundant magnetite as well as glass shards, fragments of rhyolite and chloritic material. Ordinary Light. x 27.

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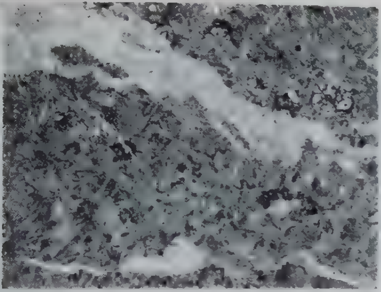
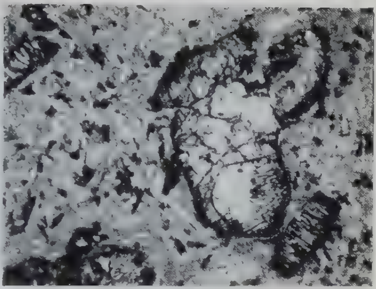
## DISCUSSION

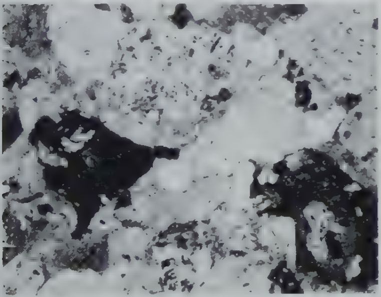
DR. A. E. MOURANT said that when, some twenty years previously, he had mapped the volcanic rocks of Jersey on the scale of six inches to a mile, it had been obvious that certain areas could be mapped adequately only on a much larger scale. One of these areas was Giffard Bay, and the mapping of this was later undertaken by Miss Casimir. Subsequently Dr. Henson collaborated in the work. The speaker congratulated the authors on the resulting map, which was extremely detailed and which he knew to reach a high standard of accuracy and completeness in its representation of field observations.



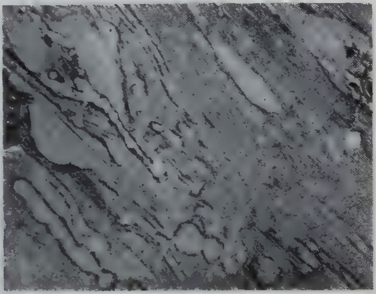
(a) 7 x



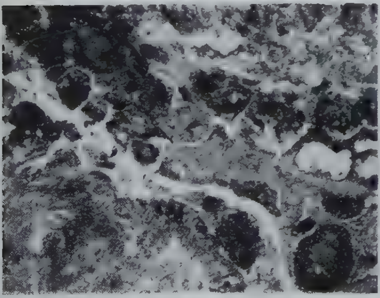
(b) 27 x



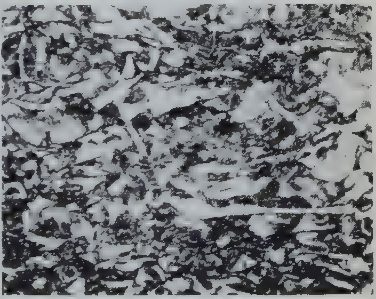
(c) 5 x



(d) 7 x



(e) 16 x



(f) 27 x

[*To face p.* 48

There were, however, a number of points of interpretation which he would like to raise. In rocks showing such rapid lateral variation as volcanics, he did not think that the area studied was large enough for the results to be used to disprove his own conclusions, based on a survey of the whole fifteen square miles of volcanic rocks of which Giffard Bay formed a part.

The inlier of andesite lava in Bonne Nuit Bay could possibly be regarded as belonging to the main andesite sequence below the rhyolites, but the speaker still preferred to consider it the product of a small late local andesitic flow. The area mapped as andesite in the middle of Giffard Bay, south of the main fault, raised greater difficulties. The speaker thought that the andesite here was entirely in the form of fragments in an agglomerate, and he asked whether the authors had found any definite andesite lava flow *in situ* at this point. The speaker knew that in the conglomerate of L'Homme Mort there was, besides much andesitic material, a little porphyritic rhyolite or porphyry. It seemed to him, however, that it was tectonically very difficult, if not impossible, to account for the presence here of rocks younger that the whole of the andesites. On most of the points mentioned he would like to take the authors' final map into the field before trying to reach a final conclusion.

DR. A. K. WELLS wished to compliment the authors on the completion of this work which was started by Miss Casimir many years ago.

Firstly, he asked what was the nature of the lava which, by disruption in a volcanic vent, could give rise to a cloud of magnetite dust?

Secondly, the authors had stated that the earliest lavas had flowed over the surface of the 'newly emerged sediments'. Yet they stated elsewhere that the lavas were separated from the sediments by an unconformity. Does the latter involve angular discordance, in which case it would imply a considerable time interval; and are there any special structural features which would support this contention, bearing in mind the fact that 'the newly emerged sediments' would be unconsolidated muds.

Finally, he asked whether the authors really believe that the present dip of the lavas at a given point can be used to establish the whereabouts of the vent from which they were erupted, in view of the fact that the lavas are believed to be of pre-Cambrian age, and that the area is part of Armorica.

DR. F. A. HENSON, in replying to Dr. A. E. Mourant, thanked him for his kind remarks and reception of a paper which covered part of the ground which he had described some twenty years earlier. The authors, whilst agreeing with the main sequence of events in the volcanics of Jersey, as described by him, had found that the volcanic and phyroclastic rocks at Giffard Bay did show a more complex and interesting history of the volcanic phase than the present literature showed. On the scale of faulting at L'Homme Mort, however, the authors' findings were very different from those of Dr. Mourant.

As regards Dr. Mourant's suggestion that the andesite at Bonne Nuit might be a small late local andesite flow, the speaker pointed out that the northern boundary of this andesite was faulted, with later rhyolites containing abundant andesite downfaulted some 200 ft. to the north, whilst at the extreme northern point of La Crête porphyritic andesite occurred, overlain by rhyolite. Further, the Bonne Nuit andesite was petrographically similar to the andesites of Long Echet. In the authors' view the andesite in the centre of Giffard Bay was *in situ*, and not a pyroclastic rock.

Finally, the speaker agreed with Dr. Mourant that it was difficult to interpret many of the agglomerates and conglomerates in the succession but that, in the sequence now proposed, all the rocks and their varied constituents had been examined petrographically. In the case of L'Homme Mort conglomerate, the authors did not consider this to be a local development of the Rozel Conglomerate.

Replying to Dr. A. K. Wells' first question, Dr. Henson stated that the Purple Shales, which are more than 60 ft. in thickness, are characterised by abundant magnetite dust. A photomicrograph of this rock had been exhibited to members earlier. The authors did not interpret this as the result of the disruption of a lava in a nearby vent to give a cloud of magnetite dust, but as the regional contamination of sediments forming under marine conditions in the vicinity of volcanic centres where the deposition of this fine dust took place at some distance beyond the zone where coarse fragmented lavas and ash occurred. They had suggested that the graded bedding in the Purple Shales reflected sporadic outbursts influencing sedimentation at considerable distances from the volcanic centre.

Regarding the second point raised by Dr. Wells, the authors maintained that in the presumed Pre-Cambrian rocks the lavas were often unconformable upon the sediments; especially in the Long Echet area. They considered that the time-interval between the outpouring of the lavas and the emergence of the sediments was sufficiently long for the sediments to have been consolidated. In the Long Echet area some of the andesites are contaminated by sediments.

In answer to Dr. Wells' last point the speaker said the authors did not hold the view that the present dip of the lavas can be used to establish the location of the vents, and disagreed fundamentally with the earlier work of Plymen upon the location of vents in this area. Furthermore, they were very much aware that this area is part of Armorica. Finally the speaker expressed his thanks to members for their reception of the paper.

# The metasediments of Bunbeg (County Donegal), and their relationship to the surrounding granite

By E. H. TIMOTHY WHITTEN

Received 6 June 1953; read 10 June 1955

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**ABSTRACT:** A detailed description is given of the petrology of a large relic of Dalradian metasediment which is completely enclosed within the Donegal Granite at Bunbeg. Particular attention is paid to the contact relations of the granite and metamorphic rocks, and evidence for metasomatism and a complex two-way diffusion is deduced.

## 1. INTRODUCTION

THE DALRADIAN ROCKS of Bunbeg have been ignored almost completely. Scott, Griffith & Haughton (1863), Forbes (1872), Nolan (in Hull, 1891, p. 72), and Zealley (1909) have made mere mention of them, and more recently Whitten (1951) has described some of the marbles and pegmatites intruded into them. Of these earlier references Nolan gives the most extensive printed account, stating that '. . . Isolated portions of mica-schist, probably caught-up masses for the most part, are not uncommon in this area, the most noticeable being that around the small village of Bunbeg. The surrounding granite sends veins and tongues into the schist, and where the rocks are in actual contact the latter often seems to have been fused. It contains remarkable beds of garnetiferous limestone with tremolite. . . .'

The extreme north-west part of Donegal consists of a series of Dalradian schists ranging in composition from quartzites to pelites and calc-silicate hornfelses. These metasediments have been invaded by the variable and composite 'Donegal Granite', which broadly comprises a migmatitic granodiorite intruded by later more potassic granites (see Fig. 1). A 'ghost-stratigraphic' sequence is contained in the migmatites of the Thorr district (Pitcher, 1952), but traced northwards into the Bunbeg district the relics of Dalradian rocks decrease in number and the granodiorite becomes much more homogeneous. The Bunbeg complex is the most northward continuation of the 'ghost-stratigraphy', and the calc-silicate hornfelses bear a close resemblance to, and are equated with, those of Annagary, south of the present area. Apart from this correlation, and the coincidence of the regional dip and lineations, the Bunbeg rocks resemble a 'roof pendant' within the regional granodiorite.

The Bunbeg metasediments comprise a compact mass with oval outline (see Fig. 2) which is traversed by the Clady River. The metamorphic rocks are largely pelitic schists with interbedded calc-silicate hornfelses and calcium-rich pelites. They are gently undulose but possess a NNW.–SSE. strike, with a regional dip of some 30°–40° ENE. The section accompanying Fig. 2 is an attempt to interpret the structure. On lithological grounds the marbles 'A' and 'D', and 'B' and 'C' appear to be equivalent, but exact correlation is made difficult because of the lithological variation and lenticularity of the different units. A pre-metamorphic basic intrusion (now epidiorite) forms a prominent knoll, known as Austin's Rock, in the centre of the area.

## 2. THE PELITES

The pelites form a relatively uniform series, although in detail there are considerable mineralogical variations. Almost invariably these rocks possess foliation parallel to the original bedding and sometimes are gneissose on a microscopic scale, i.e. micaceous bands are separated by quartzo-felspathic layers. Both the grain-size and the thickness of the bands is variable, e.g. layers of single quartz grains may be 0.06–0.20 mm. thick, and seritic or biotitic layers range from similar widths to perhaps 1.3–2.0 mm. Sometimes bands are monomineralic, but it is more frequent to find all except the quartzose bands to be more complex mineralogically. Despite a complicated series of recrystallisations, these rocks have retained some sedimentary structures with surprising faithfulness. Thus, small-scale lenticularity is frequently seen in thin section, with units 2–3 mm. thick. It might be suggested that these rocks, prior to metamorphism, possessed a structural resemblance to the Wealden shales of Atherfield Point, Isle of Wight. Numerous examples of more calcareous (hornblende–andesine–quartz), and more quartzose lenticles, alternating with the normal micaceous pelites, occur. However, it is probable that metamorphic

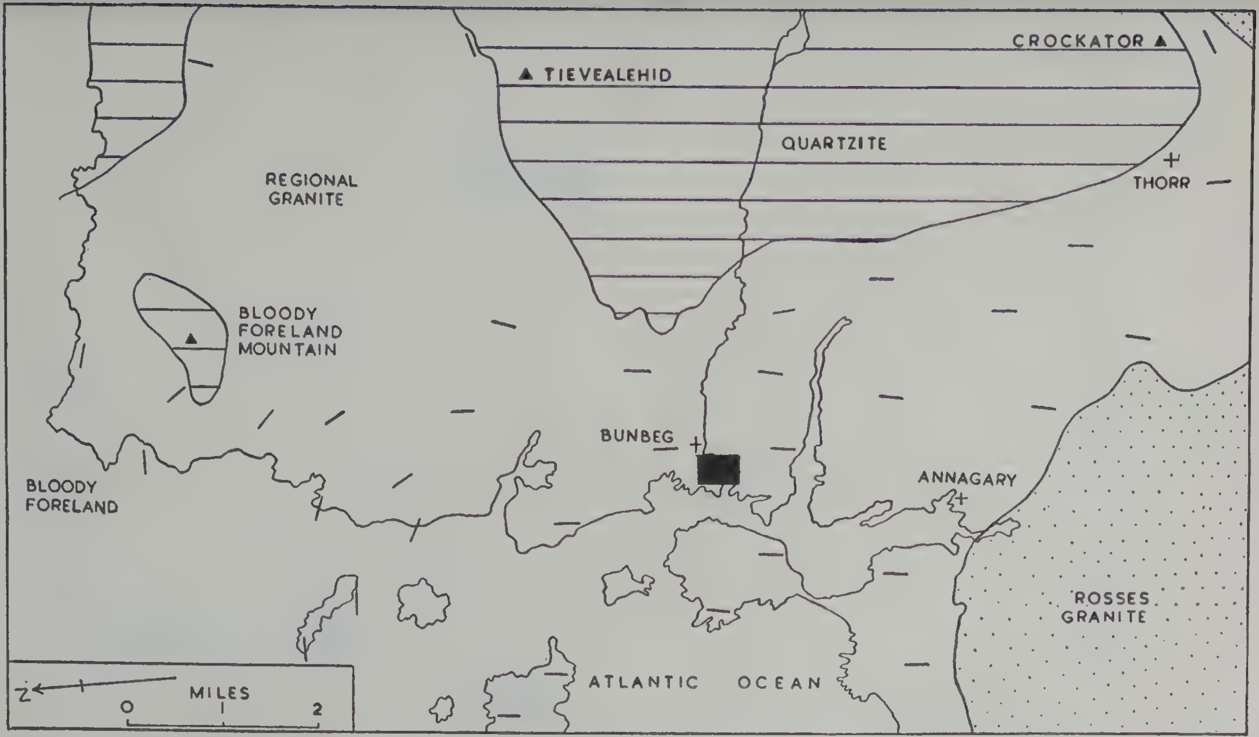

Fig. 1. Geological sketch-map of the Bunbeg area. Inset shows location of Fig. 2

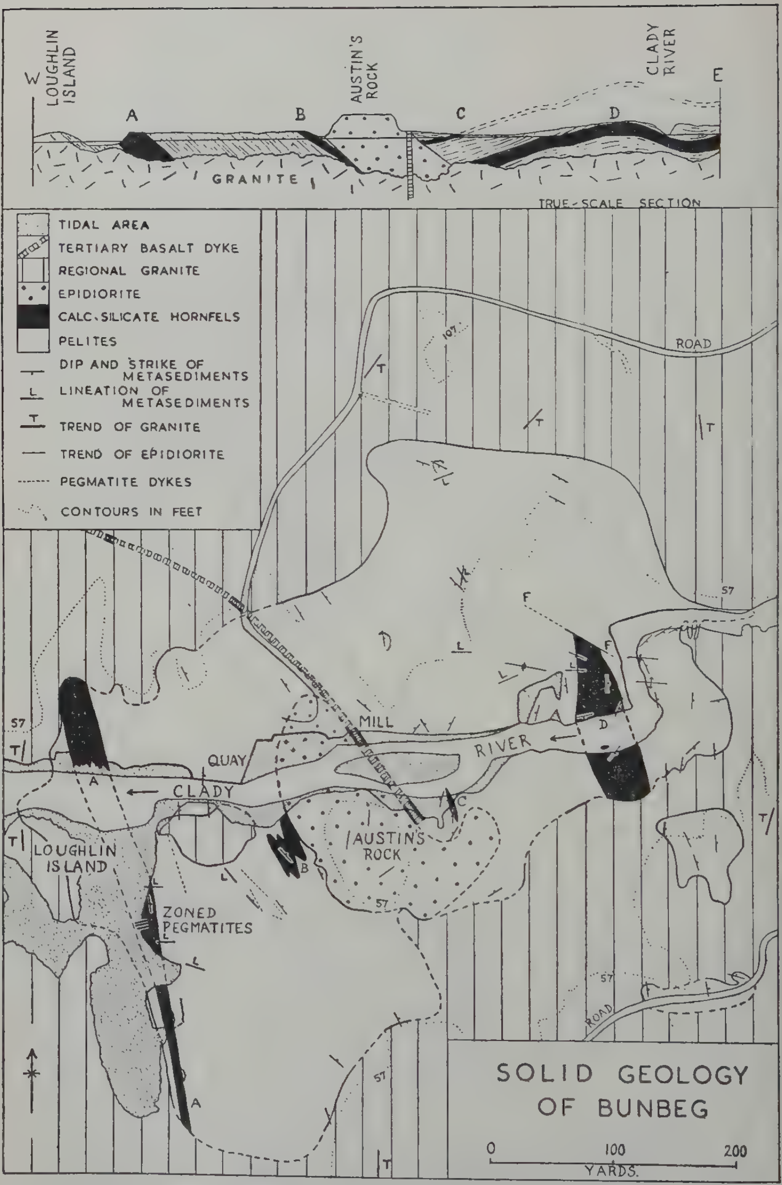

Fig. 2. Map of Bunbeg and diagrammatic true-scale section projected onto one plane

differentiation may have initiated a small proportion of the observed banding, and that this process has emphasised much of the original compositional variation and banding. This is considered further in the sequel (page 62, et. seq.).

The typical pelites in the river-cliff of Bunbeg Quay exhibit a low grade of metamorphism, the micas being a mixture of sericitic mush and leached biotites. The sericite occurs in distinct bands which occasionally penetrate between quartz grains of the adjacent layers. Dravitic tourmaline, zircon and apatite are sometimes common. Such rocks show an abundance of magnetite in the form of minute disseminated grains which are dominantly associated with, or contained in, the leached biotites from which they have been derived. Less sericitised specimens possess magnetite associated with partially penninitised and bleached biotite. These features suggest retrograde metamorphism (diaphthoresis), but, apart from the decaying biotite, no *earlier* phases of higher grade are extant.

Various higher-grade associations have begun to develop from the sericitic pelite. Thus, sieved muscovite plates develop in the midst of the sericite, and 60 yds. north-east of the zoned pegmatites (see Fig. 2) porphyroblasts of muscovite poikiloblastically enclose both biotites and quartz. Such rocks represent the first phase of recrystallisation and contain some 5% of felspar—mainly poorly twinned andesine and occasional porphyroblasts of microcline.

Representing a somewhat higher grade of metamorphism are small 'augen' of biotite which are elongated along the foliation of biotite–andalusite–muscovite–microcline–(quartz–magnetite–zircon)–schist. Such schists occur just above marble 'A' south-east of the pegmatites. Usually two generations of biotite occur as minute grains evenly distributed through the rock, and as larger grains in the 'augen'. The abundant andalusite appears as spongy grains enclosing quartz and biotite. Very occasional nests of sillimanite needles (0.18 × 0.01 mm.) occur. The replacive andalusite is very intimately intergrown with the sericite and muscovite. Eighty yards north-east of Bunbeg Quay a dominantly quartzo–feldspathic schist contains staurolite and andalusite, together with minute needles of sillimanite developing at the expense of the latter.

A complete sequence of progressive metamorphism developed from the retrograde sericitic rocks can be traced, but the actual grade is not directly related to the proximity of the granite at the level of present exposure. Thus, for example, the pelite from the northern shore of Loughlin Island is rich in pale green sericite and biotite, but also contains abundant quartz which is replacing other phases and represents a late metasomatism due to the granite. This rock does not contain any obvious microcline, such as that present in the andalusite-bearing pelites. This suggests concomitant genesis of microcline and andalusite, at the expense of sericite, in response to thermal metamorphism. No satisfactory explanation for the areal distribution of the high-grade minerals can be advanced.

## 3. THE RELATIONSHIP BETWEEN PELITES AND CALC-SILICATE HORNFELSES

Besides the small-scale lenticularity the main lithological groups are also lenticular, and transitions occur between them. The calcium-rich passage hornfelses above marble 'A' contain some very garnetiferous rocks. Thin pelite lenticles are rich in biotites. These micas, whilst oriented parallel to the bedding, have a random distribution in a rock comprising microcline, varying amounts of quartz, and occasional bands of plagioclase. Alternating with these are leucocratic bands of diopside-microcline-rock, or microcline-rock. The pyroxene occurs as small rounded or anhedral grains associated with occasional anhedra of sphene and quartz. No sericite occurs, and the microcline was mainly formed from indigenous potash. Since bands of biotite and quartz must have been interlaminated with those of calc-silicates originally, diopside and microcline could have developed under thermal metamorphic conditions in the manner suggested by Pauly's (1948, p. 334) equation, viz.:

$$\underset{\text{calcite}}{3CaCO_3} + \underset{\text{biotite}}{K(Mg,Fe)_3AlSi_3O_{10}(OH)_2} + \underset{\text{quartz}}{6SiO_2} =$$

$$\underset{\text{diopside}}{3Ca(Mg,Fe)Si_2O_6} + \underset{\text{microcline}}{KAlSi_3O_8} + H_2O + 3CO_2 \quad \text{.........(i)}$$

Microscopic examination of the several transition zones shows a number of differing mineralogical assemblages, but the abundance of microcline is a common feature, despite the variety of the rock-associations, involved. At the top of marble 'D', penninite and microcline are developed. Since:

4 biotite + 2 muscovite + 8 quartz + 4 $H_2O$ + (Mg,Fe)O =
1 penninite + 6 microcline .........(ii)

then by addition of (i) and (ii):

12 calcite + 8 biotite + 2 muscovite + 32 quartz + (Mg,Fe)O =
12 diopside + 10 orthoclase + 1 penninite + 12 $CO_2$ .........(iii)

It seems that genesis of excess microcline is restricted to the calcium-rich hornfelses, and equation (iii) suggests that only the addition of a small amount of water is required, since an excess of iron-ore is available in the pelite. Thus such a reaction could be anticipated in a virtually closed system, although the proportions of minerals and volumetric considerations necessitate slight metasomatism.

## 4. THE CALC-SILICATE HORNFELSES

The main calc-silicate hornfelses are those of marble 'A' (Fig. 2), the thickness of which approaches 40 ft. These rocks have been described in detail elsewhere (Whitten, 1951). The other marbles at Bunbeg are broadly similar to the latter and principally contain varying proportions of calcite, diopside, grossularite, idocrase and wollastonite. Throughout these marbles a long sequence of mineralogical adjustments has occurred and two distinct metamorphic phases may be recognised. Thus, small tension cracks (e.g. in marble 'D', north of the Clady River, Fig. 2) parallel to other scanty traces of lineation in the pelites and hornfelses suggest that the grossularite is a pre-tectonic, or possibly para-tectonic crystallisation, whilst diaphthoretic replacement of garnet by idocrase, and introduction of quartz and andesine are late metasomatic phenomena associated with the development of the granite (Whitten, 1951, pp. 743–4).

## 5. INTERRELATIONSHIP BETWEEN METASEDIMENTS AND THE REGIONAL GRANITE

(a) **Introduction.** The regional granite is coarse-grained and manifests considerable mineralogical variation about an average volume–composition of 28% quartz, and 62% felspar, with a colour index of 11. In the neighbourhood of Bunbeg the rock varies between quartz-biotite adamellite and granodiorite. Porphyroblastic microcline microperthites and biotite-hornblende xenoliths define a well-marked regional planar structure, which

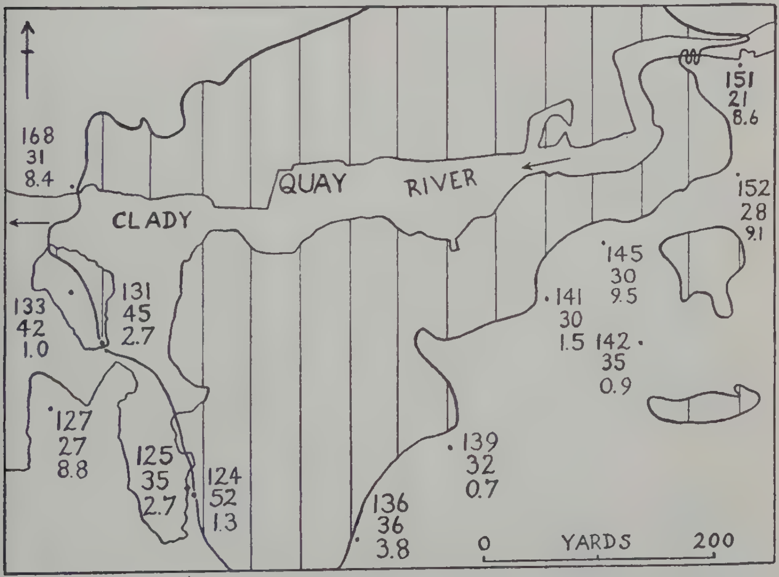

Fig. 3. Location of specimens listed in Table I. Top figure: specimen number; middle figure: quartz %; bottom figure: biotite (including penninite) %

TABLE I

| Specimen No. | 124 | 125 | 127 | 131 | 133 | 136 | 139 | 141 | 142 | 145 | 151 | 152 | 168 | 197 | J |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Quartz | 52 | 35 | 27 | 45 | 42 | 36 | 32 | 30 | 35 | 30 | 21 | 28 | 31 | 18 | 41.8 |
| Plagioclase | 33 | 23 | 34 | 8.7 | 29 | 23 | 26 | 23 | 25 | 33 | 33 | 36 | 35 | 40 | 28.3 |
| Potash Felspar | 14 | 39 | 29 | 40 | 38 | 37 | 40 | 45 | 39 | 27 | 37 | 27 | 25 | 23 | 11.9 |
| Muscovite | 0.2 | 0.2 | – | 3.0 | 0.2 | p | 0.4 | t | – | 0.1 | – | 0.1 | t | p | – |
| Biotite | 1.3 | 2.7 | 8.8 | 2.7 | 1.0 | 3.8 | 0.7 | 1.5 | 0.8 | 8.5 | 8.6 | 7.9 | 7.7 | 16 | 5.0 |
| Hornblende | – | – | – | – | – | – | – | – | – | – | – | – | – | 2.0 | – |
| Magnetite | – | – | 1.3 | 0.05 | – | – | 0.1 | 0.1 | – | – | 0.2 | 0.3 | 0.1 | 2.0 | 2.5 |
| Apatite | – | t | 0.1 | – | – | p | – | – | t | p | p | p | p | 0.5 | t |
| Orthite | – | – | – | – | – | – | – | – | – | – | 0.1 | – | 0.4 | – | t |
| Penninite | – | p(b) | p(b) | p(b) | p(b) | p(b) | – | p(b) | 0.1 | 1.0 | p | 1.2 | 0.6 | – | – |
| Zircon | – | p | – | t | – | – | – | p | t | 0.1 | t | – | 0.1 | p | – |
| Sphene | – | – | p | – | – | – | – | – | t | – | 0.1 | – | p | – | – |
| Colour Index | 1.5 | 2.8 | 10 | 5.7 | 1.3 | 3.8 | 1.2 | 1.7 | 0.9 | 9.6 | 9.0 | 9.1 | 8.8 | 20 | 7.5 |

Locations of specimens are indicated on Fig. 3.

Sp. 124: quartz-adamellite (calc-alkaline)

Sp. 125, 133, 136, 139, 141, 142: quartz-adamellite (potassic)

Sp. 127, 145, 151, 152, 168: biotite-quartz-adamellite

Sp. 131: quartz-potash-granite

Sp. 197: biotite-adamellite (potassic), a quarter of a mile up-stream from Bunbeg metamorphic rocks

J : the most quartz-rich granodiorite listed by Johannsen (1931, p. 339)—quartz-rich granite from Amsdorf, Germany

t = trace; p = present; p(b) = present but included in biotite becomes less apparent, or is macroscopically invisible, in the immediate vicinity of the metasediments. The mafic xenoliths are discoidal and analogous to the autoliths of Holland (1900) and Pabst (1928), but are absent close to the metasediments of Bunbeg.

The granites near the metasediments are extraordinarily rich in modal quartz (see Table I). Certain of these values have been plotted in Fig. 3. From this it will be seen that the highest quartz values relate to those rocks closest to the contact, and the quartz percentages can almost be used as an index of proximity. Fig. 3 also shows that volumetrically, biotite bears an antipathetic relationship to quartz, and this is further emphasised by Table II, which has been compiled from the figures contained in Table I. (It should be noted that this relationship is maintained up to the actual contact, at which there is an accumulation of biotite, as described below.)

Further analysis of the modes indicates that the quartz percentage in the potassic adamellites and calc-alkaline adamellites is not significantly different, as is demonstrated by Table III.

(b) **Petrography of the contact-zone granites.** These rocks have a notably uneven distribution of minerals. Felspar is aggregated together, quartz segregated and the biotite associated in groups or clots of subhedral crystals. The noticeable inhomogeneity of hand-specimens is mainly due to the enclosure of small biotite clots which are apparently xenolithic. A few other probable xenolithic fragments sometimes occur. These comprise

TABLE II: **Granites associated with the Bunbeg Metasediments, arranged in order of decreasing quartz percentage.**

| Specimen No. | Quartz % | Penninite and Biotite % | Colour Index | Total % of Felspar |
|---|---|---|---|---|
| 124 | 52 | 1.3 | 1.5 | 47 |
| 131 | 45 | 2.7 | 5.8 | 49 |
| 133 | 42 | 1.0 | 1.3 | 67 |
| 136 | 36 | 3.8 | 3.8 | 60 |
| 142 | 35 | 0.9 | 0.9 | 54 |
| 125 | 35 | 2.7 | 2.8 | 62 |
| 139 | 32 | 0.7 | 1.2 | 67 |
| 168 | 31 | 8.4 | 8.8 | 60 |
| 141 | 30 | 1.5 | 1.7 | 68 |
| 145 | 30 | 9.5 | 9.6 | 60 |
| 152 | 28 | 9.1 | 9.1 | 63 |
| 127 | 27 | 8.8 | 10 | 63 |
| 151 | 21 | 8.6 | 9.0 | 70 |
| 197 | 18 | 16 | 20 | 63 |

TABLE III: **Analysis of modes given in Table I**

| Calc-alkali Adamellites | | | Potassic Adamellites | | | Potash Granite | | |
|---|---|---|---|---|---|---|---|---|
| Specimen No. | Quartz % | K. Felspar % | Specimen No. | Quartz % | K. Felspar % | Specimen No. | Quartz % | K. Felspar % |
| 124 | 52 | 14 | 125 | 35 | 23 | 131 | 45 | 8.7 |
| 127 | 27 | 29 | 133 | 42 | 29 | | | |
| 145 | 30 | 27 | 136 | 36 | 23 | | | |
| 152 | 28 | 27 | 139 | 32 | 26 | | | |
| 168 | 31 | 25 | 141 | 30 | 23 | | | |
| | | | 142 | 35 | 25 | | | |
| 197 | 18 | 23 | 151 | 21 | 33 | | | |
| Average of 5 | 34 | 24 | Average of 7 | 33 | 26 | Average of 131 and K. Adamellites | 35 | 24 |

closely-aggregated small grains of quartz and plagioclase, riddled with vermiculate filaments resembling micro-runite (or myrmekite).

The *biotite* is variable in colour, with

$$\left.\begin{array}{r}\alpha=\beta=\text{straw yellow}\\ \gamma=\text{dark sepia}\end{array}\right\}\text{or occasionally}\left\{\begin{array}{l}\text{very pale yellow-brown}\\ \text{very rich chestnut red-brown}\end{array}\right.$$

It is partially altered to penninite, with concomitant generation of magnetite and/or sphene. Inclusions of apatite, zircon, sphene and orthite occur. Where biotite decreases at the expense of quartz it is often slightly corroded by the latter, and where the quartz-content is very high the biotite occurs as small ($<0.4$ mm. long) strongly-leached, or wholly- or partially-penninitised individuals.

*Muscovite* is generally absent, except for some 3 % present at the southern end of Loughlin Island. Previously (1951, p. 763) it has been pointed out by Whitten that this rock is traversed by the shatter-zone containing the late zoned pegmatites (across the creek from the Island), and that it has probably undergone a late metasomatism which appears to have leached the iron and magnesium from the biotite allowing the generation of muscovite.

The *plagioclase* varies between albite-oligoclase and more basic oligoclase, and the euhedral to subhedral grains show oscillatory zoning. Differential alteration of these zones to 'white mica', kaolinite, and clinozoisite has occurred. Two phases of growth are indicated by the fact that small crystals are enclosed in both larger plagioclases and microclines.

Two phases of *microcline* growth can also be separated in some of these rocks; an earlier, characterised by the development of microcline microperthites with marked quadrille twinning, is the more abundant; and a later, during which untwinned microperthites were formed. The latter partially replace both the earlier twinned microcline and plagioclase, and also form sinuous areas between earlier minerals.

Although it is difficult to deduce a chronology, and despite the fact that there has probably been considerable overlap between the different stages, the following order of felspar crystallisation may be suggested:

(i) the poikilitically enclosed small euhedral plagioclases
(ii) large plagioclase crystals } probably overlapping or
(iii) large twinned microcline microperthites } contemporary development
(iv) 'deuteric' albite, increasing the previously exsolved perthite films and partially enveloping some of the plagioclases
(v) myrmekite (time in sequence uncertain)
(vi) untwinned microcline replacing twinned microcline.

The whole of this series is not always present in any one rock.

The *quartz* is largely interstitial. Invariably it replaces other phases and frequently contains miscellaneous concave fragments of felspar which are undoubtedly palimpsests of largely replaced grains. In granites with the lower quartz-content it has caused corrosion along intercrystal boundaries, but with added modal quartz large bulbous incursions into adjacent grains occur, and there is an increased number of small microcline palimpsests set in the quartz areas. That is, the quartz is more replacive and large sinuous bulbous masses (crowded with bubbles) have corroded all the felspars. Such large quartz 'crystals' (often 1 cm. long) are frequently composed of units which are more or less in optical continuity, but, nevertheless, seem to be composed of grains imperfectly welded together. This replacement was not effected in a single 'wave' because some of the quartz is interstitial to other quartz.

Table II shows that Specimen No. 141 has an unusually low quartz-percentage, both from a consideration of its geographic position and its biotite-content. Actually, this specimen is peculiarly rich in potash felspar, having the highest percentage (45%) of any in this series. Microscopic examination confirms this anomaly, because the quartz replacement and sieving are of the highly bulbous type, comparable with that of rocks with a considerably higher content of quartz.

## 6. SUMMARY OF THE GRANITE RELATIONSHIPS AND PETROGENESIS

It is clear that the modes of these contact granites illustrated, show definite trends, as shown by the percentage of mafic minerals which diminishes towards the metasediments, so that the corresponding colour index decreases from about 9.3 to 2.7. This decrease is antipathetic with respect to the increase in quartz from 28% to 42% within the same series of rocks. (Figures are the averages for Specimens Nos. 151, 127, 152, 145 and 168, and for 125, 142, 131 and 124 respectively.)

As the colour index (9.3) of the granites outside the leucocratic zone is smaller than that of the granites lying still farther afield, the rocks close to Bunbeg appear to have been 'leached' of ferro-magnesian constituents, which might be assumed to have entered the metasediments. It may be argued that this evidence supports a granitisational hypothesis, because in such a process basification would precede granitisation (e.g. see Reynolds, 1946), implying that the ferro-magnesian constituents of the contact zone would pass into the xenolithic rocks, and in their wake, acidification would take place. However, if these Bunbeg xenolithic rocks are indeed a residual mass of a partially granitised complex, it is difficult to explain why the granite again becomes rich in iron and magnesium away from the 'leached' leucocratic zone, and also why a superabundance of replacive quartz is not found in those granites well removed from the metasediments.

It seems more probable that these metasediments comprise a true relic of the roof-zone of the granite 'cauldron' about which the somewhat plastic granite has 'washed'. The latter process is envisaged to be one in which the granite, shortly prior to final consolidation, underwent plastic flowage about this large xenolithic mass. Such a plastic condition would undoubtedly encourage migrational interchange between the metamorphic rocks and the immediately adjacent granite. Since the former constituted a concentration of cafemics—particularly biotite—it would have attracted the biotitic constituents away from the marginal granite to the immediate contact zone by a process of segregation during metamorphic differentiation analogous to that described for biotite (and staurolite) by Chapman (1950) in the quartz-staurolite-veins in the Claremont Quadrangle (W. New Hampshire, U.S.A.). However, although the latter example has been conceived as proceeding in a closed system not requiring any substantial volume change, such conditions did not obtain at Bunbeg.

While the removal of biotite can easily be accounted for, the origin of the quartz is problematical, because it has neither been wholly derived from the metasediments, nor from the 'material' uniformly passing through, and being arrested in, the surrounding granite. Detailed studies of the surrounding areas show that there was indeed a regional focus of quartz-enrichment and microcline-enrichment to the north-west of Bunbeg from which quartz-generating media dispersed. Although late replacive quartz is thus characteristic of the whole of the granite, it is never so superabundant as round the Bunbeg metamorphic rocks. It is considered that the combined operation of the following two processes has given rise to the observed distribution:

(a) The distinctive banding of the metasediments (of non-calc-silicate type), in which discrete and well-defined mafic and leucocratic bands occur, strongly suggests that metamorphic differentiation has strengthened the original compositional variations. Relatively high energy levels, similar to those favouring such a diffusion, would also be likely to favour two-way diffusion about the 'contact zone', allowing a considerable amount of potential quartz to be released. Most of the pelites still possess appreciable quartz, but the diffusing silicon would tend to enrich the more quartzose granite. This would imply that the margin of the metasediments constitute a basic residue (or the 'basic behind' of H. H. Read). Table II indicates that the volumetric quartz-content of the granite has been increased from about 28 % to 42 %, which, in view of the narrowness of the quartz-enriched zone, probably does not represent more than could have been derived from the metasediments.

(b) At Bunbeg most of the mineralogical modifications of the metasediments relate to migration of (OH) affecting the micas and aluminium silicates. However, there is evidence of small-scale quartz-enrichment of both the epidiorites of Austin's Rock, and the previously developed quartzose bands of the pelites. Also, quartz occasionally appears to replace and vein earlier replacive quartz in the peripheral granite. Scattered evidence of this sort suggests the introduction of, and replacement by, exotic quartzose materials in both the granitic and metamorphic rocks subsequent to the initial diffusion processes. All this chemical activity appears to have enabled an exceptionally large amount of quartz-generating constituents to be trapped in the contact zone. These constituents would probably pass more easily through the developing plastic granitic materials than through the metasediments—especially the marbles and epidiorites. Hence constant dispersion through the regional granite would tend to cause an added accumulation against the partial barrier of the metamorphic rocks.

It is thus suggested that an early phase of metamorphic differentiation within the metasediments, and two-way diffusion between them and the granite, was followed by a regional quartz-enrichment of all the rocks, including the granite about Bunbeg and, to a limited extent, the metamorphic rocks.

In some respects the metamorphic rocks simulate the laminated schists of Otago (New Zealand) which Turner (1941) has shown to have developed from the massive Te Anau and Tuapeka Series as a result of metamorphic differentiation. In this case, Turner has pointed out that the region is believed to be underlain at depth by a major granitic intrusion, and thus it is admitted that addition of magmatically-derived material, especially silica, may have supplemented the process of differentiation in the development of quartz-rich lamellae. However, Turner considers this to be, at most, a subordinate process. Whereas these Otago schists have largely undergone internal reorganisation and possibly subsidiary quartz-soaking, the Bunbeg rocks have undergone similar processes and also a more important and extensive interaction with surrounding rocks.

At the actual contacts the pelitic rocks do not exhibit the marked lamellar structure characteristic of the highly differentiated rocks. This is taken as additional evidence for the existence of a definite basic residue which has been leached of leucocratic materials, rather than that these biotite-rich portions are ‘basic fronts’. If they were in fact ‘basic fronts’ presumably they should be found along most, or all, of the peripheral portions of the granite mass. It is significant, however, that this mafic concentration is not associated with the quartzite-granite contacts of the area (e.g. Whitten, 1953, Table I), although it is universally present marginal to contacts with ferro-magnesian rocks. The biotites comprising this mafic selvedge are relatively large, indicating the ready availability and abundance of the constituent materials. The mafic materials moving towards the metamorphic rocks from the granite would tend to concentrate at the junction of the two rock-types, thus accentuating the already-existing basic residue.

In the preceding discussion it has been assumed that the granite would have been approximately homogeneous (as it is in adjacent areas) in the immediate vicinity of Bunbeg if it had not been affected by the metasediments. Likewise, it has been assumed that initially the metamorphic rocks had a broadly similar character throughout. It would be unreasonable to suggest that this was not so, but the argument does not depend on any assumption of identical chemical or mineralogical composition. Indeed, the precise nature of the concentration of mafic constituents at the immediate margin of the metamorphic rocks is dependent on the adjacent country rock, which is additional evidence in support of the concept of a basic residue rather than a 'basic front'.

In summary it may be stated that the contact-relations differ from those which would be expected with basification followed by granitisation. They are, however, consistent with genesis by metamorphic differentiation, followed (possibly penecontemporaneously) by regional quartz-soaking. It is hoped to discuss the regional aspects of this acidification of the granite in a subsequent paper.

The expenses incurred in this work have been defrayed by a grant from the Central Research Funds of the University of London, which grant is gratefully acknowledged. The useful criticism given by Dr. A. K. Wells is also acknowledged.

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## APPENDIX

After reading the paper before the Geologists' Association, the author mentioned that the work described had been completed in 1951 and early in 1952, whilst the manuscript had been submitted to the Association during 1953. At the time when the paper was prepared the results obtained (with the Dollar Integrating Stage Micrometer) seemed to be sufficient and adequate. The modes for specimens 133 and 139 were determined after the original hypothesis was evolved and, being perfectly harmonious, seemed to confirm the hypothesis.

Since submitting the paper, however, new techniques for rapid point counting and chemical analyses have been developed, and in terms of these it was admitted that the quantitative data presented were inadequate. However, the author was confident, from his field observations and study of other unmodalised specimens, that in this case an increased number of high-quality modal analyses would leave the basic hypothesis unchanged, and would merely give greater precision to the quantitative data upon which it was based.

## DISCUSSION

DR. W. S. PITCHER congratulated the author on his useful contribution to Donegal geology, adding that it was often necessary to describe small areas in detail so that they might serve as general examples. Dr. Whitten had rightly pointed out the limitations of his own modal analyses but there was no doubt that semipelitic rafts within the 'Older Granodiorite' were often bordered by modified granitic rocks (cf. *Q.J.G.S.*, **108,** 428) similar to those described from Bunbeg; the biotite-enriched zone was, however, not always so clearly shown as at this locality. An hypothesis implying reciprocal exchanges of material, including the subtraction of silica from the metasediments, was an attractive one but the speaker asked whether, if this were indeed the mechanism, the thickness of the biotite selvedge was in proper proportion to the much greater width of the quartz-enriched contact facies.

On a minor point Dr. Pitcher said that he supposed the muscovitic aggregates seen in thin sections of the metasediments, to be after sillimanite. He asked whether, in possible confirmation of this, these particular white micas included granules of iron oxide or were associated with bleached biotites.

MR. E. L. P. MERCY criticised the use of the term 'diffusion'. It was generally held that diffusion implied movement of ions along a concentration gradient. Since the $Si^{4+}$ concentration in the raft was probably of the same order as that of the original granite, and the concentrations of $Fe^{2+}$ and $Mg^{2+}$ were much higher in the raft than in the original granite, diffusion was an unlikely event. Indeed, if the conditions had been right for diffusion, then $Fe^{2+}$ and $Mg^{2+}$ would have migrated into the granite. Obviously, some other mechanism ought to be postulated.

DR. A. T. J. DOLLAR congratulated the author on a most interesting presentation of an intriguing series of petrogenetic problems. Particularly he welcomed the full modal information on which Dr. Whitten had based a number of his arguments, although some of the chemical inferences drawn from these data by Dr. Whitten were, in his opinion, susceptible of interpretations other than those suggested.

Across contacts such as had been described there was a very real need for much more quantitative mineralogical determination than had been customary hitherto. Especially in connection with igneous rock-variation, this had been stressed by H. L. Alling (*Interpretative Petrology of the Igneous Rocks*, New York, 1936, 336). On this account it was gratifying to the speaker to know that his integrating micrometer had played its part in gathering, by the Rosival method, the modal information presented in this paper. Even if Dr. Whitten had chosen to obtain his modes by the rapid point-count, or Glagolev method, to which he referred, a minor modification of the same micrometer, described by Dr. Dollar to the Mineralogical Society on 25 March 1954, would have enabled Dr. Whitten to employ the instrument as a point-counter with equal efficacy.

THE AUTHOR thanked Dr. Pitcher for his remarks. In the paper the sericite mush is referred to as a product of diaphthoresis, and it is frequently associated with bleached biotite and/or iron ore granules. No trace of *original* fibrolite (sillimanite) has been detected at Bunbeg, but there is no reason why fibrolite might not have been present as a product of the original regional metamorphism.

Dr. Whitten said that he was glad Dr. Pitcher concurred with the view that the textures shown on the screen are peculiar and undoubtedly indicate replacement. The extreme difficulty of interpreting such textures, and, in particular, of determining the direction in which the replacements were proceeding, is admitted. It was only intended to illustrate the striking textural evidence for very extensive mineralogical replacements having occurred within the granitic rocks marginal to the contacts; such textures corroborate the more direct evidence for readjustment and replacement.

The relative width of the biotitic selvedge and the quartz-enriched zone which is to be expected, raised an interesting, but almost imponderable, question. Firstly, it is impossible to make an accurate three-dimensional quantitative assessment of the problem. Secondly, particularly with respect to Si, it seemed unlikely that it was justifiable to think solely in terms of a closed chemical system. However, confidence was expressed in the validity of the basic residue hypothesis, and the appropriateness of the size of the biotitic selvedge observed at Bunbeg.

By 'diffusion' in the black-board drawing a simple homogenising process was not intended, as suggested by Mr. Mercy; rather 'metamorphic diffusion' which had accentuated the original lithological boundaries was implied. Eskola's well-established concretion principle in metamorphic differentiation is thought to have been operative, and this principle has previously been invoked in connection with the 'bleaching' of granitic gneiss in contact with more mafic rocks, and in numerous analogous relationships.

The author thanked Dr. Dollar for his remarks, and said that he agreed with him in stressing the need for much more quantitative data. Recently the need for an abundance of accurate and rapidly-determined chemical analyses had been emphasised, but it seemed to be *equally* necessary to press for much more detailed study and recording of accurate modal compositions and variations in all petrological work.

# Borehole Records from the Lea Valley between Cheshunt and Edmonton

by J. F. HAYWARD

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**ABSTRACT:** The results of thirty-six trial bores in the Lea Valley, between Cheshunt and Edmonton, are described. They show that, in this area, the Reading Beds and London Clay are thrown up into an anticlinal fold with its axis at Brimsdown.

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DURING THE EARLY PART of 1951 the author was privileged, through the courtesy of the Middlesex County Council, to obtain information about a series of trial boreholes made in the Lea Valley in connection with the East Middlesex Main Drainage Scheme. Twenty-three boreholes were involved, from near Brimsdown Station to Deephams Sewage Works, Edmonton. In many cases the author was present during the boring, and he was also allowed access to the samples obtained by the contractors. About two years later fresh boring was carried out. This consisted of thirteen somewhat shallower boreholes sunk along a line stretching north from Brimsdown to Cheshunt Sewage Works near Waltham Abbey, a total distance of about four miles, as shown in Fig. 1. A cluster of eight borings at Deephams Works were also involved, but are not included in this description. Although he was not present during the boring of the second group, the author was allowed access to all records and sample-boxes relating to this operation. Also he was permitted to retain specimens, when necessary. The boreholes were numbered from 219 (Deephams) to 201 (at Brimsdown) and from 220 (Brimsdown) to 233 south of Cheshunt; No. 228 was not bored.

The formations examined were:

Superficial deposits
Flood-Plain Gravel of the River Lea
London Clay
Reading Beds

**Reading Beds.** These were seen in boreholes 213 to 201 and 220 to 223. In 220, in Millmarsh Lane, Enfield, the top of the Reading Beds underlies the river gravel at a depth of 20 ft., i.e. at approximately 30 ft. O.D., the beds being brought up to this level in an anticlinal fold. The northern limb of this fold is steeper than the southern limb. The Reading Beds in this area are divisible into three series:

(c) Mottled Clays, passing down into sands with some pebbles
(b) Clays and pebble beds
(a) Glauconitic sands, with or without pebbles (? Bottom Bed)

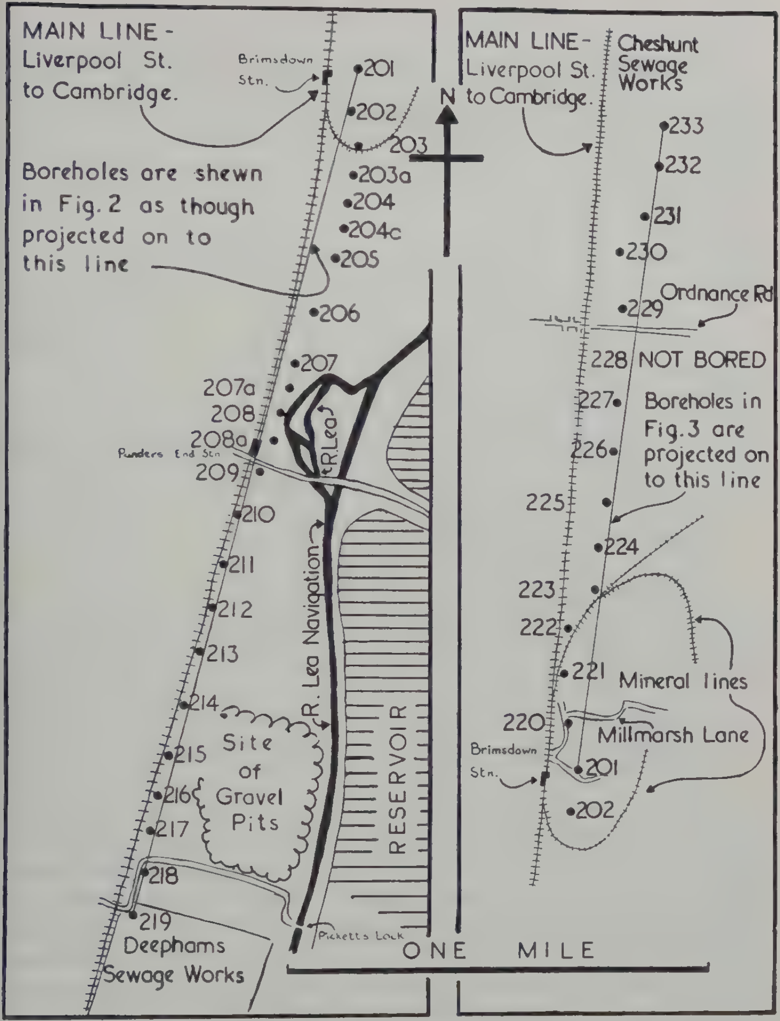


Fig. 1. Distribution of the boreholes

The presumed Bottom Bed was found only in boreholes 202, 201, 220 and 221 at the extreme base. It consisted of fine angular quartz-sand with some clay, and green glauconitic grains of which some appeared to be internal casts of foraminiferal tests. At the base of 201 the bed contained pebbles.

The sand was followed by a series of clays, or sandy clays, with or without pebbles, which were seen typically in boreholes 207 to 201 and 220 to 221. These were generally grey or black clays or laminated clays, sometimes almost approaching lignite, and sometimes containing pebbles. At places they were interbedded with grey, sandy clays. They attained a thickness of 18 ft. in borehole 201.

The uppermost series was typical grey or blue-grey mottled clay with yellow, brown or red inclusions. In the lower part, the clays passed down into sands, or sandy clays.

The Reading Beds were best seen in borehole 201 where the following succession was noted:

| | | | |
|---|---|---|---|
| Deposits above the Reading Beds | | | 26 ft. |
| Pale blue mottled clay | 2 ft. | Mottled Clay | 9 ft. |
| Pink mottled sandy clay, with soft sandstone nodules | 2 ft. | | |
| Red sandy clay, with soft sandstone nodules | 1 ft. | | |
| Grey mottled clay | 2 ft. | | |
| Grey mottled sandy clay, with hard ferruginous sandstone nodules | 2 ft. | | |
| Pebble bed, with clay matrix | 7 ft. | Pebble Beds and Clays | 18 ft. |
| Grey sandy clay | 5 ft. | | |
| Pale grey sandy clay | 1 ft. | | |
| Greenish-grey sand | 4 ft. | | |
| Pebble bed, with clay matrix | 1 ft. | | |
| Grey sand | 2 ft. | Bottom Bed seen to | 7 ft. |
| Grey sand, with pebbles, seen to | 5 ft. | | |

In the Mottled Clay Series certain mineral phenomena were observed. They indicated either progressive infiltration of ferruginous matter in a downward direction, or, alternatively, progressive removal of such matter in an upward direction. The five highest beds of the Reading Series mentioned above illustrate this fact, which is also seen in borehole 208a (see below) where blue-grey mottled clay, with yellowish streaks, passes down into a grey sand with yellowish inclusions. Ferruginous segregations were seen in the mottled clay of boreholes 210 and 211 but in 201, 220, 221 and 222 hard ironstone-concretions were observed.

**London Clay.** This lay on the irregular surface of the previous formation. South of Brimsdown it consisted of two parts, a grey or grey-brown sandy clay at the base, and a grey or blue-grey non-sandy clay above. Certain of the sandy layers contained glauconitic streaks and there was a well-marked band of lenticular patches, some distance above the base, which showed a bright green colour due to glauconite. There was no reason to believe that the sequence north of Brimsdown was any different from that already detailed, but adequate records are not available.[1] In boring 213 the green band contained fragile lamellibranch shells. It was not possible to identify the Basement Bed in many boreholes but about 2 ft. of grey sandy clay, with small irregular pebbles and fragile fossils, was observed in borehole 201. On the other hand, in borehole 208a a core was obtained showing the junction of the fossiliferous Basement Bed with the Reading Beds below. Small fragments of shells were found in the lowest 1 ft. 6 in. of the London Clay in borehole 204a.

Small irregular pyrite nodules were found in some boreholes, and have been indicated by the letter P in Fig. 2. In borehole 204a one such nodule was a lamellibranch cast resembling *Cyprina* sp. No other fossils were identifiable except that some were seen to be lamellibranchs.

In only one borehole (215) was the surface of the clay found to be weathered brown to a depth of 1 ft. In all others the surface was blue-grey or grey. In some, pebbles were included in the surface of the clay, and if they were not carried down by the boring tool—the more probable explanation—they indicate some disturbance of the surface during the deposition of the gravel. The lower surface of the clay was reached just above Ordnance Datum in borehole 213, but had not been encountered at −14 ft., O.D. in borehole 214, only about 250 yds. to the south. This represents a sudden steepening of the southern limb of the anticline into which the beds are folded. At the highest point of the fold (borehole 220) the London Clay is completely absent, and the river gravel rests directly upon Reading Beds. This is partly due to the fact that the river valley has been cut a little more deeply at this point than in adjacent places.

**The flood-plain gravel of the River Lea.** This consisted of a grey or buff sandy gravel composed of sub-angular flints, up to an inch or two in diameter, with a high proportion of rounded quartz pebbles, and some rounded sandstones and quartzites. The gravel had a matrix of rounded or sub-rounded quartz grains, with rarer sub-angular flint grains. In a few boreholes some small pellets of clay were found within the gravel but no recognisable deposits corresponding to the Ponders End Arctic Bed were encountered in the main series of borings. However, it is possible that some small elongated nodules of indurated sand, found in the middle of the gravel in borehole 230, may indicate the position of this bed.

**Superficial deposits.** These generally consisted of 3 to 6 ft. of grey, brown or yellow clay, or loam, or an admixture of one of these with pebbles. They presented no special features.

A summary of the results of the boring is given in Figs. 2 and 3. Certain of the borings were watched, foot by foot, by the author, and the details of these are given below.

---

[1] Subsequent tunnelling operations have proved that these sub-divisions do apply both north and south of Brimsdown, and that whereas the upper division is impervious to water, the lower division is not.

### BOREHOLE 204A

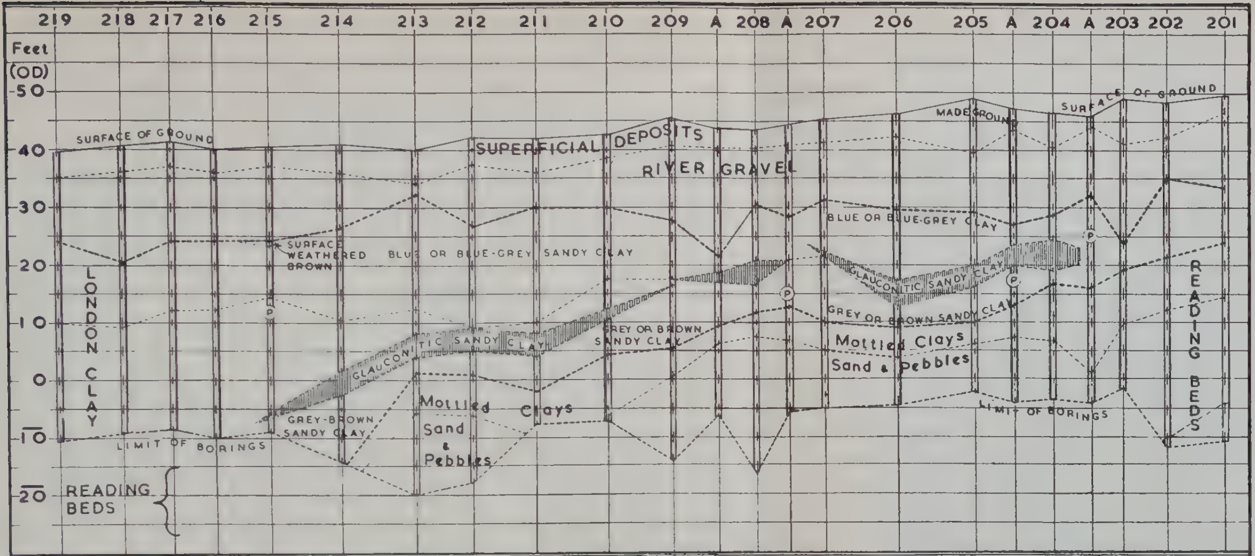
| | | | |
|---|---|---|---|
| Brown clay | | | 4 ft. 0 in. |
| River gravel | | | 16 ft. 0 in. |
| Grey clay | 4 ft. 0 in. | London Clay | 14 ft. 6 in. |
| Glauconitic sandy clay | 3 ft. 0 in. | | |
| Grey sandy clay | 6 ft. 0 in. | | |
| Grey sandy clay, with fragments of shells. (? Basement Bed) | 1 ft. 6 in. | | |
| Blue-grey mottled clay | 5 ft. 6 in. | Reading Beds seen to | 15 ft. 6 in. |
| Pebbles and sand | 8 ft. 0 in. | | |
| Black laminated clay | 6 in. | | |
| Black clay with pebbles, seen to | 1 ft. 6 in. | | |

### BOREHOLE 207A

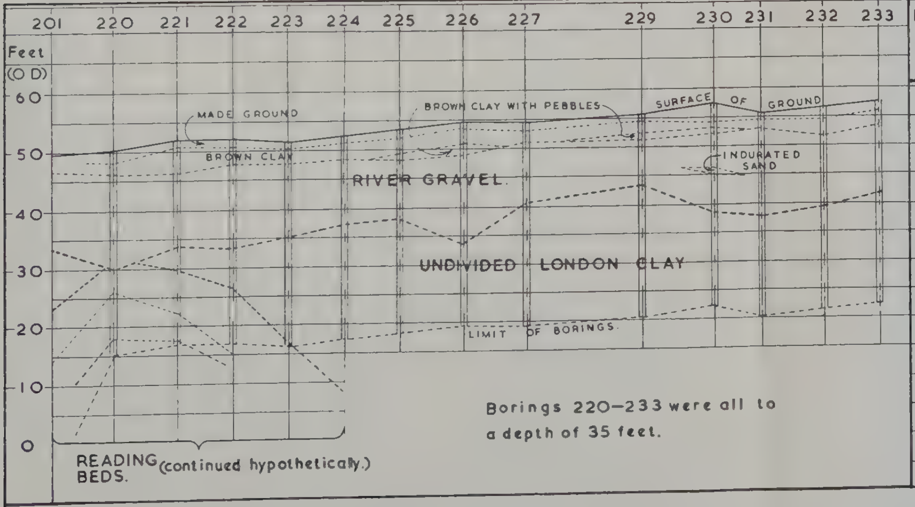
| | | | |
|---|---|---|---|
| Soil | | | 1 ft. 0 in. |
| Brown clay | | | 1 ft. 0 in. |
| Brown clay and pebbles | | | 1 ft. 6 in. |
| River gravel | | | 12 ft. 6 in. |
| Grey sandy clay | 5 ft. 0 in. | London Clay | 16 ft. 0 in. |
| Grey clay | 3 ft. 0 in. | | |
| Brownish sandy clay, with pyrite nodules | 8 ft. 0 in. | | |
| Bluish mottled clay | 3 ft. 0 in. | Reading Beds seen to | 18 ft. 0 in. |
| Grey sandy clay with yellow patches | 3 ft. 0 in. | | |
| Grey sand | 4 ft. 0 in. | | |
| Light grey clay and pebbles (sandy in patches) | 5 ft. 0 in. | | |
| Grey sand and pebbles, seen to | 3 ft. 0 in. | | |

### BOREHOLE 208A

| | | | |
|---|---|---|---|
| Soil | | | 1 ft. 0 in. |
| Brown clay | | | 1 ft. 0 in. |
| Brown clay and pebbles | | | 1 ft. 0 in. |
| River gravel | | | 18 ft. 6 in. |
| Grey clay with pebbles | 6 in. | London Clay | 12 ft. 6 in. |
| Grey clay | 3 ft. 0 in. | | |
| Glauconitic sandy clay | 2 ft. 0 in. | | |
| Grey sandy clay with streaks of glauconite, fragile fossils, and yellow clay nodules | 7 ft. 0 in. | | |
| Blue-grey mottled clay, with yellowish streaks | 3 ft. 6 in. | Reading Beds seen to | 16 ft. 0 in. |
| Grey sand with yellowish inclusions: narrow band of pebbles at base | 6 ft. 6 in. | | |
| Clayey sand, passing down into clayey, laminated sand, seen to | 6 ft. 0 in. | | |



| Borehole No | Approx National Grid Reference | Top of Boring. OD | Depth of Borehole in feet. |
|---|---|---|---|
| 201 | 51/364970 | 49.58 | 60 |
| 202 | 364968 | 48.10 | 60 |
| 203 | 364967 | 48.78 | 50 |
| 203a | 364966 | 46.00 | 50 |
| 204 | 364965 | 46.67 | 50 |
| 204a | 364964 | 47.26 | 50 |
| 205 | 364963 | 48.81 | 50 |
| 206 | 363961 | 45.63 | 50 |
| 207 | 362959 | 45.34 | 50 |
| 207a | 362958 | 44.46 | 50 |
| 208 | 362957 | 43.61 | 60 |
| 208a | 51/362956 | 43.73 | 50 |
| 209 | 361955 | 45.43 | 60 |
| 210 | 360953 | 42.39 | 50 |
| 211 | 360951 | 41.79 | 50 |
| 212 | 359949 | 41.90 | 60 |
| 213 | 358947 | 39.89 | 55 |
| 214 | 358946 | 40.71 | 50 |
| 215 | 357944 | 40.63 | 50 |
| 216 | 357943 | 40.0 | 50 |
| 217 | 357941 | 41.23 | 50 |
| 218 | 357939 | 40.41 | 50 |
| 219 | 357937 | 39.43 | 50 |



| Borehole No | Approx National Grid Reference | TOP OF BORING OD |
|---|---|---|
| 220 | 51/3649725 | 50.2 |
| 221 | 364974 | 51.8 |
| 222 | 364976 | 51.8 |
| 223 | 365977 | 51.3 |
| 224 | 365979 | 52.3 |
| 225 | 365981 | 53.5 |
| 226 | 366983 | 54.7 |
| 227 | 366985 | 54.2 |
| 229 | 366988 | 55.4 |
| 230 | 366991 | 57.2 |
| 231 | 367992 | 55.2 |
| 232 | 367994 | 56.6 |
| 233 | 367995 | 57.4 |

Fig. 2 (above) and Fig. 3 (below). The disposition of deposits in the boreholes, with intermediate details estimated. The positions of the boreholes have been projected onto straight lines joining the extreme boreholes of each group. 'P' indicates the presence of pyrite.

### BOREHOLE 215

| | | | |
|---|---|---|---|
| Yellowish-brown clay and pebbles | | | 1 ft. 0 in. |
| Brown clay | | | 1 ft. 6 in. |
| Red-brown clay and pebbles | | | 1 ft. 0 in. |
| Yellow sandy gravel | | | 6 ft. 6 in. |
| Greyish gravel | | | 6 ft. 0 in. |
| Brown clay | 1 ft. 0 in. | London Clay seen to | 34 ft. 0 in. |
| Grey clay | 9 ft. 0 in. | | |
| Grey sandy clay with some pyrite | 5 ft. 0 in. | | |
| Alternations of sandy and non-sandy fissile clay | 15 ft. 0 in. | | |
| Bright green glauconitic sandy clay | 1 ft. 0 in. | | |
| Sandy clay with glauconitic streaks and occasional fragile fossils | 2 ft. 0 in. | | |
| Grey clayey sand (bearing water) seen to | 1 ft. 0 in. | | |

The author desires to thank representatives of the Middlesex County Council for permission to examine the borehole-records and to publish this account, and the Council's Consulting Engineers, Messrs. J. D. and D. M. Watson, M.M.I.C.E., and their Resident Engineer, the late Mr. A. Good, for giving every facility. Mr. S. E. Ellis, B.Sc., F.G.S., and Mr. S. Hazzledine Warren, F.G.S., kindly discussed certain aspects of the material with the author who is indebted, also, to the late Mr. F. W. Hough, for preparing the drawings from which Fig. 2 and Fig. 3 were made.

Corallian Beds, which are exposed in the cliff. Along the middle of the cove, from the sea northward to Preston and beyond, the Jurassic rocks are overlain by the Holocene alluvium of the River Jordan (Arkell, 1947, pl. XIX).

## 2. THE QUATERNARY DEPOSITS

(a) **Previous records.** The Quaternary deposits at this locality have been referred to briefly by Strahan (1898) and by Arkell (1947, p. 350); a legend relating to the cliff-section at Bowleaze shown on pl. IX of Strahan's memoir mentions the occurrence of 'Elephant remains found here under rain-wash', on the east side of the cove. Fisher (in Prestwich, 1875) had already noted elephant remains found on the shore at 'Preston' (i.e. Bowleaze), at low water. Damon (1864 and 1884) described a deposit of yellow loam containing land and marine mollusca, exposed in the cliff on the east side of the cove. Arkell does not mention these records, but refers to 'a few feet of dark alluvial clay full of recent land and fresh-water snails, capped by a few feet (variable) of recent stream gravel', seen here, in the banks of the Jordan stream. Miss Keef (in Farrar, 1949) has described a Romano-British occupation layer and probable refuse ditches, at Bowleaze, and records some marine mollusca from the former, but no other animal remains.

(b) **Present sites.** The sites examined for the purposes of this paper were: (1) the low cliff on the western side of the cove, showing an Early Holocene loam overlain by the Romano-British layer, with a Holocene tufaceous loam between the two at one point; (2) the cliff on the eastern side of the cove, showing at least three distinct Quaternary deposits; (3) the stream-sections along the banks of the River Jordan, showing the Holocene alluvium of that stream, and (4) a small area at the back of the beach, on the eastern side of the cove, showing a brown Holocene loam, examined in October 1953 when free from shingle.

The following four sites were selected for making minor excavations in the east and west banks of the stream. Excavation I was in the left (east) bank about 17 yds. SSW. of the old stone bridge over the Jordan, this bridge being about 73 yds. NNE. of the beach. Excavation IA was in the opposite bank at the same locality, and Excavation II was in the left bank about 44 yds. SSW. of Excavation I. Excavation III was in the same bank, where the stream meanders eastwards through the beach for several yards, the site of this excavation being about 7 yds. south of the landward (northern) edge of the beach, and about 17 yds. south of Excavation II.

The positions of the seven sites, and eight deposits, are shown in the sketch-map (Fig. 1) and measured cliff-section (Fig. 2).

(c) **Deposits examined by the author.** These are as follows:

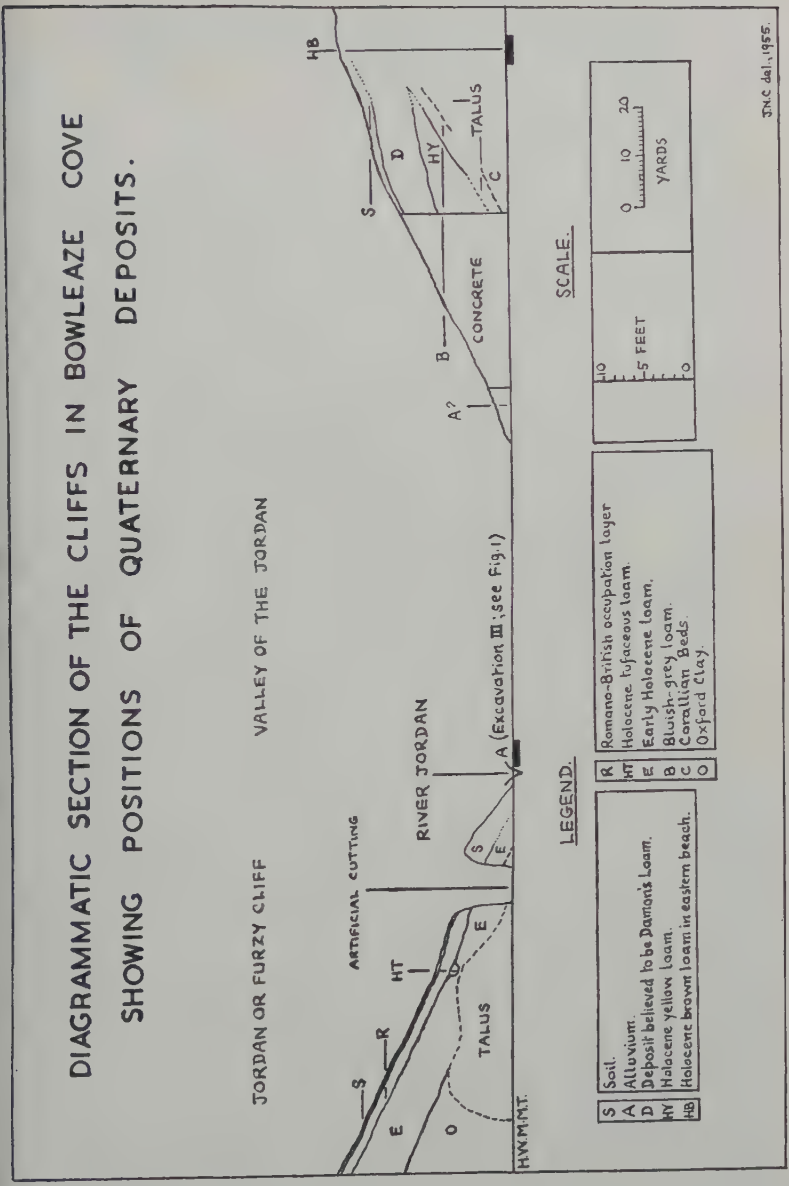

DIAGRAMMATIC SECTION OF THE CLIFFS IN BOWLEAZE COVE
SHOWING POSITIONS OF QUATERNARY DEPOSITS.
JORDAN OR FURZY CLIFF
VALLEY OF THE JORDAN
ARTIFICIAL CUTTING
RIVER JORDAN
A (Excavation III; see Fig. 1)
S
R
HT
E
O
TALUS
H.W.M.M.T.
A?
B
CONCRETE
S
D
HY
C
TALUS
HB
LEGEND.
S Soil.
A Alluvium.
D Deposit believed to be Damon's Loam.
HY Holocene yellow loam.
HB Holocene brown loam in eastern beach.
R Romano-British occupation layer
HT Holocene tufaceous loam.
E Early Holocene loam.
B Bluish-grey loam.
C Corallian Beds.
O Oxford Clay.
SCALE.
10
5 FEET
0
0 10 20
YARDS
J.N.C del., 1955.

Fig. 2

viii. Holocene alluvium of the Jordan
vii. Deposit believed to be Damon's Loam
vi. Holocene yellow loam with limestone and sandstone debris
v. Holocene brown loam in the beach at the eastern end of the cove
iv. The Romano-British occupation layer
iii. Holocene tufaceous loam
ii. Early Holocene loam
i. Bluish-grey loam with sandstone debris.

Deposits (i) to (vii) show no distinct subdivisions, but (viii) consists of a series of beds, as described below under (k), and tabulated in a generalised form in Fig. 1.

(d) **The bluish-grey loam with sandstone debris.** This is a bluish-grey sandy loam, with fragments of grey sandstone or fine grit and juvenile valves of Jurassic oysters. The loam is not clearly bedded, and its constituents are somewhat angular and poorly sorted. Washed residues of this deposit consist almost entirely of pieces of grey sandstone or fine grit, with some Jurassic shell-fragments, but a few very small tubular calcareous concretions, and rare fragments of oolite, occur. Tests of an arenaceous foraminifer, *Ammobaculites* sp., found and determined by Mr. A. G. Davis, are common in these residues, and in his opinion are derived from the Jurassic, but no contemporaneous (Pleistocene or Holocene) organic remains have been found in the loam. The deposit is exposed in the cliff on the east side of the cove, from about 114 to about 127 yds. east of the Jordan stream, being seen to a thickness of 1 ft. 6 in., but its base is hidden by talus. Its surface lies about 6 ft. 6 in. above beach level, and is overlain by the Holocene yellow loam with limestone and sandstone debris described below. Both deposits seem to be banked up against the Corallian rocks which form the eastern side of the Jordan valley at this locality. Structurally, the bluish-grey loam resembles both the yellow loam, and the Early Holocene loam on the western side of the cove, but the available evidence does not support any close comparison. The poorly-bedded and ill-sorted appearance of the bluish-grey loam, and the presence in it of grey sandstone or fine grit fragments, valves of Jurassic oysters, and many tests of *Ammobaculites*, suggest that it is a sludge or hill-wash, composed principally of the debris of nearby Jurassic (most probably Corallian) sandstones. The deposit is clearly of Pleistocene or Holocene age, but no more precise estimate of this is possible in the absence of contemporaneous fossils. It may be noted that Barnard (1953, pp. 184–5) has described two species of *Ammobaculites* from the Oxford Clay (*C. cordatum* Zone) of Redcliff Point at the eastern termination of Bowleaze Cove.

(e) **The Early Holocene loam.** This deposit is a light grey argillaceous loam, mottled with hydrated ferric oxide, and full of ooliths and angular pieces of limestone up to about 6 in. in length. Although it contains much calcareous material, this is not extremely finely-divided and intimately mixed with the clay-fraction, as in a marl, but only in the form of ooliths, limestone and calcite fragments, molluscan shells and calcareous concretions. Washed residues consist of oolite, ooliths and small fragments of calcite. Many Oxfordian (Upper Jurassic) oysters are present, both whole and fragmentary. The deposit weathers to a brownish-cream colour, or buff tint. It is obscurely bedded, and its constituents are not well-sorted. Nearly all the flat pieces of limestone are seen to rest horizontally. Other pieces lie obliquely, and it is to be noted that in places the loam shows signs of disturbance by solifluction after its formation, this having affected the imperfect original stratification. In some places calcareous concretions, or 'race' nodules, up to half an inch in diameter occur sparingly in the upper two feet of the loam. From about 30 to about 40 yds. west of the Jordan stream the deposit passes down into very stiff blue-grey clay with race nodules, this clay being seen to a thickness of about one foot, but its base is obscured by talus. The loam has been detected only in the low cliff on the western side of the cove, west of the Jordan; it is not seen in the stream-sections, and is in no way associated with the stream. It is seen to a maximum thickness of five feet, its upper surface then reaching a height of 13 ft. 6 in. above beach level, at a point in the cliff about 69 yds. west of the Jordan, the most westerly point to which it has been traced, but the cliff decreases in height eastward to the stream, so that about 8 yds. west of the latter the upper surface of the loam is only seen to a height of about 2 ft. 10 in. above the beach, and probably extends below the shingle, to an unknown depth. It is overlain throughout the length of this section of the western cliff by the Romano-British occupation layer, although at one point a depression in its surface, beneath the latter, is filled with the Holocene tufaceous loam mentioned above, and described later. Where the base of the Early Holocene loam is visible it is underlain by the Oxford Clay.

The stiff blue-grey clay with race nodules, mentioned above as occurring directly beneath the Early Holocene loam, has only been seen to underly a thickness of about two feet of the latter, the thickness nearby being considerably greater, and it is probable that the clay is merely a local downward continuation of the loam, rather than a distinct deposit. The ooliths and limestone fragments in the loam are obviously derived from Corallian limestones in the district, and the argillaceous material forming much of the loam may be from Corallian clays, Oxford Clay, or both. Contemporaneous organic remains appear to be confined to the top 7 to 18 in., and have only been obtained from that part of the cliff extending from about 25 yds. to about 38 yds. west of the Jordan stream. By washing samples of the loam the following non-marine mollusca, and fragments of vole teeth (Carreck, 1955, p. 167), have been recovered. The determinations of the mollusca, and notes upon them, have been made by Mr. Davis, who, in listing them, has followed the taxonomic arrangement given in the

'Census of the distribution of British non-marine mollusca' (Ellis, 1951), and has adhered to this practice in subsequent lists given in the present paper. At least thirty-five species of mollusca are represented in the following list. For comparative purposes a list of nineteen species of non-marine mollusca prepared by Mr. Davis from material collected by him in 1954 from the white Holocene tufa at Spring Bottom near Ringstead in Purbeck (Arkell, 1947, p. 352 and pl. XIX) is placed beside the Bowleaze list; it is the first faunal list for this deposit to be published. In considering the faunal lists in this paper it should be noted that they are based on material obtained from unequal samples of deposits examined by the author, or from unknown quantities obtained by other investigators. Therefore, for comparative purposes the numbers tabulated here should be considered only in the form of percentages of the total number of individual shells found in the deposit from which they were obtained, so that these percentages, and the qualitative composition of the assemblages, are the criteria to be used in comparing and contrasting the faunal lists.

### FAUNAL LIST FOR THE EARLY HOLOCENE LOAM

compared with that for the white Holocene tufa at Spring Bottom near Ringstead

| | | Bowleaze | Spring Bottom |
|---|---|---|---|
| | MAMMALIA | | |
| *Microtus* sp. indet. | Fragments of molars | 2 | – |
| *Clethrionomys* ? sp. indet. | | 1 | – |
| | MOLLUSCA | | |
| *Valvata piscinalis* (Müller) | | 1 | – |
| *Pomatias elegans* (Müller) | | 10 | 1 |
| *Carychium minimum* Müller | | 19 | – |
| *C. tridentatum* (Risso) | | 3 | C |
| *Lymnaea truncatula* (Müller) | | 6 | – |
| *L. peregra* (Müller) | | 1, very small | – |
| *Planorbis leucostoma* Millet | | 1 | – |
| *P. crista* (Linné) | | 2 | – |
| *Succinea oblonga* Draparnaud | | 50 | – |
| *S. pfeifferi* Rossmässler | | 7 | – |
| *Cochlicopa lubrica* (Müller) | | 5 | 1 |
| *Columella edentula* (Draparnaud) | | 2 | – |
| *Vertigo pusilla* Müller | | 2 | 3 |
| *V. antivertigo* (Draparnaud) | | 14 | – |
| *V. pygmaea* (Draparnaud) | | 11 | – |
| *Pupilla muscorum* (Linné) | | 10 | – |
| *Acanthinula aculeata* (Müller) | | 8 | 4 |
| *Vallonia costata* (Müller) | | 2 | 17 |
| *V. pulchella* (Müller) | | 22 | – |
| *V. excentrica* Sterki | | – | 4 |
| *Clausilia bidentata* (Ström) | | 31 | – |
| *Cecilioides acicula* (Müller) | | 3 | 20 |
| *Helix hortensis* Müller | | 1 | 2 |

| | Bowleaze | Spring Bottom |
|---|---|---|
| *H. nemoralis* Linné ... ... ... ... | 10 | Fragments |
| *Hygromia hispida* (Linné) ... ... ... | 2 | 6 |
| *Monacha granulata* (Alder) ... ... ... | 18 | – |
| *Punctum pygmaeum* (Draparnaud) ... ... | 5 | 2 |
| *Discus rotundatus* (Müller) ... ... ... | C | 22 |
| *Arion* sp. or spp. (granules) ... ... | C | C |
| *Euconulus fulvus* (Müller) ... ... ... | 2 | – |
| *Vitrea crystallina* (Müller) ... ... ... | 11 | 12 |
| *Oxychilus cellarius* (Müller) ... ... | 3 | 12 |
| *Retinella radiatula* (Alder) ... ... ... | 3 | 1 |
| *R. nitidula* (Draparnaud) ... ... ... | 2 | 2 |
| *Limax* spp. ... ... ... ... ... | C | 1 |

Numerals denote numbers of specimens found.
C=Common.

Although this deposit bears some superficial resemblance to the Late Pleistocene Head and Loam at Portland Bill, about 9½ miles SSW. of Bowleaze, a closer comparison shows that they differ widely as regards fauna (Kennard & Woodward, 1901, pp. 246, 258–60) and lithology, whilst the molluscan fauna of the Bowleaze deposit has little in common with that known from the Neolithic of Maiden Castle near Dorchester (Kennard, in Wheeler, 1943), even when the aquatic species in the former are disregarded, and the only deposit with which the Bowleaze loam appears to be comparable, as regards fauna, is the white tufa at Spring Bottom, the mollusca of which are listed above. The age of the Spring Bottom white tufa appears to be Early Holocene and its fauna is not unlike that of the Blashenwell tufa, of Late Mesolithic age (probably Atlantic, according to C. Hawkes)[1] (in Arkell, 1947, pp. 351–2).

From the molluscan evidence Mr. Davis regards the Early Holocene loam as having accumulated on a former land surface, a marsh with adjacent woodlands and subject to occasional flooding, in a climate most probably damper than at present. From this information, together with the fact that the mollusca also show that this is not a fluviatile deposit, and since it is only poorly-bedded, its constituents are not sorted, and it contains large angular limestone fragments, it would appear to be the result of accumulation of water-saturated rock-debris on low-lying ground, the material presumably having been derived from the adjacent hills.

The probability that the loam extends below beach level suggests considerable antiquity, and the deposit is overlain by the Romano-British occupation layer. In a depression in the surface of the Early Holocene loam a deposit of tufaceous loam of Iron Age or Roman date occurs, as previously mentioned, and described later (p. 85). Therefore no part of the Early Holocene loam can be later in date than the end of the Roman period. It has been affected by solifluction after its accumulation, and since this phenomenon—prevalent in the English periglacial area during the Pleistocene and earliest Holocene—did not take place after the earlier part of the Mesolithic period, this deposit cannot be younger than that time. The present writer originally considered the loam to be either Late Pleistocene or Early Holocene (Carreck, 1955, p. 167), but only the latter view is now seen to be correct, since the molluscan fauna shows neither evidence of a cold climate existing at the time of deposition of the loam nor any undoubted Pleistocene elements, whilst it is not comparable with the Late Pleistocene molluscan fauna of the Head and Loam at Portland Bill, as mentioned above. Indeed, the abundance of species and individuals, in the upper part of the Early Holocene loam, in comparison with the other Quaternary faunas known from Bowleaze, suggests an optimum of climate at the end of the time of its formation. Therefore, in view of all these considerations, it is not improbable that the Bowleaze loam was formed during an early phase of the Mesolithic period, but further evidence is needed in this connection.

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[1] Hawkes' opinion was based on his examination of the flint industry, but Bury (1950, p. 51), on other grounds, suggests a late Boreal date.

**(f) The Holocene tufaceous loam.** This is a grey tufaceous and argillaceous loam, containing abundant calcareous nodules and tubes, from about 2 mm. to 6 cm. or more in length. It is not a true tufa, such as occurs at Blashenwell near Corfe, in Purbeck. Laboratory examination showed that the deposit consisted mainly of a brownish-grey clay with Quaternary non-marine shell-fragments and calcareous nodular material. The only arenaceous matter present was very fine sand, the grains of which were only recognisable under the microscope. The particles of clayey material between the concretionary and organic fragments showed no evidence of a carbonate on treatment with dilute hydrochloric acid. Therefore the deposit is not a marl, but an argillaceous loam with calcareous nodular material and molluscan shells. Washed residues contain abundant race-nodules and many shell-fragments, with some angular to well-rounded quartz grains, subangular fragments of flint or chert, fragments of oolite, nodular ironstone, rare ooliths and sandstone. Among the non-marine shell-debris a fragment of a valve of *Cardium* ? sp. indet. was noted.

As already mentioned, this deposit fills a shallow depression in the surface of the Early Holocene loam, about 6 ft. in width and about 8 in. in depth, beneath the Romano-British occupation layer. It occurs in the low cliff on the western side of the cove, extending from about 38 yds. to about 40 yds. west of the Jordan stream, and its upper and lower surfaces are at 5 ft. 11 in. and 5 ft. 3 in. respectively, above the beach. As this depression is seen only in section, its form and extent are doubtful, although the floor is manifestly flat and the walls nearly vertical. The deposit is not a lateral continuation or variant of the Early Holocene loam, since it is clearly separated from that deposit both below and to right and left, having a limited width and thickness. Palaeontological and archaeological evidence in support of this contention is given below.

Molluscan shells are abundant and well preserved in the tufaceous loam, with the colour-banding still present in the helices, but all are fragile, particularly the examples of *Helix aspersa* which, though common, readily fall to pieces. Twenty-eight species of non-marine mollusca are represented in the deposit and, according to Mr. Davis, constitute a terrestrial fauna but indicative of sodden ground supporting *Pisidium* sp. The Field Vole, *Microtus agrestis* (L.), of which a tooth was found, is essentially a graminivorous species, but little importance can reasonably be attached to the presence of a single specimen. The two shells of *Littorina* found in the loam are evidently human food-debris, such as occurs commonly in the Romano-British layer. The only archaeological objects known from the loam are two small much-worn potsherds found *in situ*. Mr. R. A. H. Farrar, F.S.A., of the Royal Commission on Historical Monuments, has been kind enough to examine these and all other pieces of pottery mentioned in this paper, and reports upon those from the tufaceous loam as follows. 'These . . . are scraps of blackish sandy ware with some larger grits of shaley appearance. . . . Unfortunately they are quite indeterminate. In paste and finish, as far as one can judge the latter in their abraded condition, they appear to be normal Romano-British coarse ware, but I would not be prepared to state that they could not be just pre-Roman. In any case they are not likely to be earlier than about 50 B.C. or much later than about A.D. 400.'

Lithologically, this deposit resembles the undescribed grey tufa directly below the also undescribed Mediaeval layer at Spring Bottom, near Ringstead, according to Mr. Davis, but not the Blashenwell tufa, or the white tufa at Spring Bottom already discussed. A comparison of the molluscan fauna of the tufaceous loam with other Holocene molluscan assemblages in the district shows that it has much in common with that from the Iron Age levels at Maiden Castle, near Dorchester, listed by Kennard (in Wheeler, 1943), and still more so with that from the grey tufa at Spring Bottom and from the Romano-British occupation layer at Bowleaze, but not with that from the Blashenwell tufa. It differs considerably from that of the Early Holocene loam, whilst human food-debris is represented by shells of *Littorina* in the former, but no trace of it was found in the latter.

The following lists give the seventeen, or more, species of mollusca which Mr. Davis has determined from material he collected from the grey tufa at Spring Bottom in 1953, and the twenty-eight species determined by him from samples of the Bowleaze tufaceous loam, obtained by the present writer in the same year. No faunal list for the former deposit has been published previously. Mr. Davis has also contributed the record of *Littorina* sp., noted by him in the writer's samples.

### FAUNAL LIST FOR THE HOLOCENE TUFACEOUS LOAM
compared with that for the grey Holocene tufa at Spring Bottom near Ringstead

| | Bowleaze | Spring Bottom |
|---|---|---|
| MAMMALIA | | |
| *Microtus agrestis* (Linné) | A damaged left $m_{I}$. | – |
| MOLLUSCA | | |
| *Pomatias elegans* (Müller) | Fgts. | – |
| *Carychium minimum* Müller | 59 | 3 |
| *C. tridentatum* (Risso) | – | 4 |
| *Lymnaea truncatula* (Müller) | 5 | – |
| *Succinea oblonga* Draparnaud | 9 | – |
| *S. putris* (Linné) | 6 | – |
| *Cochlicopa lubrica* (Müller) | 3 | 3 |
| *Vertigo antivertigo* (Draparnaud) | 4 | – |
| *V. pygmaea* (Draparnaud) | 16 | 2 |
| *Lauria cylindracea* (da Costa) | 10 | – |
| *Vallonia costata* (Müller) | 2 | 40 |
| *V. pulchella* (Müller) | 2 | 26 |
| *V. excentrica* Sterki | 1 | 13 |
| *Clausilia bidentata* (Ström) | 8 | – |
| *Cecilioides acicula* (Müller) | 2 | 191 |
| *Helix nemoralis* Linné | 4 + fgts. | 3 |
| *H. aspersa* Müller | 3 + fgts. | – |
| *Hygromia hispida* (Linné) | 25 | 52 |
| *Monacha granulata* (Alder) | 4 | – |
| *Helicella virgata* (da Costa) | 3 | 2 |
| *Discus rotundatus* (Müller) | 55 | 15 |
| *Arion* sp. or spp. | Rare | C |
| *Vitrea crystallina* (Müller) | 13 | 4 |
| *Oxychilus cellarius* (Müller) | 3 | 12 |
| *Retinella radiatula* (Müller) | 6 | 3 |
| *R. nitidula* (Draparnaud) | 5 | 2 |
| *Limax* sp. | 3 | – |
| *Pisidium* sp. | 8 | – |
| *Littorina* sp. | 2 | – |
| *Cardium* ? sp. indet. | 1 fgt. | – |

Fgts. = Fragments

From this assembled evidence the following conclusions may be drawn. The deposit was clearly accumulated in a water-logged depression where there was no running water, as shown by the presence of the damp-loving genus *Succinea*, and *Lymnaea truncatula*, but only one truly aquatic form. An abundance of calcium bicarbonate in solution in water rich in dissolved carbon dioxide, or lime-secreting freshwater algae present in sufficient numbers, resulted in the deposition of calcium carbonate on twigs or brushwood lying in the water, and calcareous nodules formed round other nuclei in a similar manner. Subsequent decay of the wood within the calcareous incrustations left them as tubes of varying size, as found in the deposit. The molluscan shells generally have a calcareous incrustation, and traces of this were also found on one of the potsherds obtained from this loam. The latter accumulated in a cavity or channel in the Early Holocene loam, but has no other connection with it and is of much later date. A human occupation-site or rubbish-accumulation occurred close by, and a few objects from it entered the site where the tufaceous loam was forming. The deposit was formed in a congenial climate (as shown by the abundance of species and individuals in its molluscan fauna) either at the end of the Iron Age or during Roman times. Its presence directly beneath the Romano-British occupation layer, dated to the fourth century A.D. from evidence discussed later, shows that the loam had ceased to form before the end of that century. The worn condition of the two potsherds found in it may be due to their having been transported by a stream before entering the water-logged depression. The possibility that the sherds had entered it from the Romano-British layer appears to be precluded by their eroded condition. This latter is similar to that of some water-worn sherds from the fine alluvial gravel (Bed ii) in Excavation I, described later, which contrasts with the unworn or little worn condition of the sherds found *in situ* in the Romano-British layer, although it is possible that those found in the tufaceous loam were worn by moving down into it from the Romano-British layer. The view that they are contemporaneous with the tufaceous loam appears to be further supported by the fact that no trace of any sherd or other archaeological object has been found in the top of the Early Holocene loam which similarly underlies the Romano-British layer, and is of far greater extent, and it would be remarkable if sherds had moved downward in an area only six feet in width and had not done so in an adjacent area having a width of many yards.

(g) **The Romano-British occupation layer.** This has been described previously by Miss Keef (in Farrar, 1949), who has recorded limpet, oyster and cockle from it, but states that ‘no bones at all’ occur; a view now found to be untenable. The deposit is a nearly black argillaceous loam with flint pebbles, pieces of sandy limestone and oolite, scattered potsherds, shells of edible marine mollusca, and a few bones and teeth of domestic animals. Its thickness varies from 6 to 8 in. and it has only been detected on the western side of the cove, where it appears in the low cliff, overlying the Early Holocene loam and Holocene tufaceous loam, and overlain only by turf. It may be traced westward for a distance of at least 68 yds. in the cliff from just above beach-level, close to the west bank of the Jordan stream, to a point where its upper surface reaches a height of 14½ ft. above beach-level. It has no obvious connection with the Jordan stream.

A series of potsherds, obtained from this layer by the present author between 1952 and 1953, has been studied by Mr. Farrar, who has furnished the following report. 'The collection comprises about 90 sherds, . . . in every way typical of Roman sites in the region. Most . . . [are] probably of local provenance, and there are few certain or likely imports from outside the Dorset region. The material is . . . very fragmentary, although it is significant that the recognisably later pieces are generally substantial, the recognisably earlier ones small, as if they had been lying about for some time before their inclusion in the deposit. A considerable proportion consists of amorphous fragments of the common coarse sandy culinary ware, not closely datable in their present condition, or of forms that underwent little change throughout the Roman occupation. . . . Fragments definitely referable to the late Roman period, and on which the dating of the deposit depends, are seven pieces of finer, slip-coated ware (including four folded beakers or "thumb-pots") such as were produced in the New Forest kilns, and which may be referred to the fourth century A.D. They are nearly all of hard grey paste with a grey or brown dull slip. None of these shows the high metallic gloss that has been regarded as characteristic of the New Forest products from *c.* A.D. 330 onwards, but it would be unwise . . . to suggest that they could not belong to the latter part of the century. Possibly as late, although the type begins in the late second century, are three fragments of coarse ware conical bowls with flanged rims. A half-dozen typical everted rims, approaching the cavetto profile, from normal coarse ware cooking pots, are too fragmentary for precise determination, although one or two . . . suggest . . . [a] third or fourth century [date]. The remainder of the datable sherds are of less significance, as they must be regarded as rubbish survivals in so late a deposit, and so do not affect its dating . . . [but] must reflect earlier occupation in the vicinity. Amongst these are three scraps of imported "Samian" ware (including Dragendorff's form 37), probably of second century date, and some coarse ware fragments of native pot forms which, though characteristic of the early Roman occupation of the south-west, may have continued in manufacture much later than has generally been supposed. These include two fragments of counter-sunk-handled jars, and several bead-rims. Other than the Samian, no characteristically early Romanised types are recognisable, although some pieces of softer buff-coloured ware could belong to flagons or jugs of quite early date. . . . The [collection thus] includes several sherds of fourth-century slip-coated ware of New Forest type, and some relatively late coarse ware, as well as rubbish survivals of earlier date including a little Samian ware and native coarse forms. The deposit may therefore be regarded as of fourth century date.'

The following organic remains have been obtained from this deposit recently; the determinations of the twenty-five species of non-marine mollusca are by Mr. Davis. For comparative purposes a list of thirty-five species of such mollusca determined by him, and two species of mammals, from the Romano-British layer overlying the Mesolithic tufa at Blashenwell, is placed with this. The Blashenwell list has been prepared from material collected in 1953 by Mr. Davis' brother, Mr. N. F. Davis, and is the first faunal list for that deposit to be published, with the exception of the records of *Helix aspersa*, *H. virgata*, and *H. ericetorum* (= *Helicella itala* (L.)) given by Reid (1896, p. 69). The marine mollusca listed here from Blashenwell are also quoted from page 69 of Reid's paper. *Helicella itala* does not appear in the present list.

## FAUNAL AND FLORAL LIST FOR THE ROMANO-BRITISH LAYER

compared with that for the Romano-British layer at Blashenwell

| | Bowleaze | Blashenwell |
|---|---|---|
| MAMMALIA | | |
| *Bos.* sp. (small form) | Distal part of right calcaneum | Shaft of tibia |
| *Ovis* or *Capra* | Part of left mandibular ramus, a lumbar vertebra, and two cheek teeth | Cheek tooth |
| *Sus scrofa* Linné | Right lower canine | — |
| MOLLUSCA | | |
| *Pomatias elegans* (Müller) | 6 | 300 |
| *Bithynia tentaculata* (Linné) | 5 opercula | – |
| *Carychium minimum* Müller | 5 | 916 |
| *Lymnaea truncatula* (Müller) | 4 | 1 |
| *L. peregra* (Müller) | – | 3 |
| *Planorbis planorbis* (Linné) | – | 1 |
| *P. vortex* (Linné) | – | 2 |
| *P. leucostoma* Millet | 2 | – |
| *P. crista* (Linné) | 3 | 1 |
| *Segmentina complanata* (Linné) | 1 | – |
| *Succinea* sp. | – | 1 |
| *S. oblonga* Draparnaud | 7 + {many juveniles | – |
| *Cochlicopa lubrica* (Müller) | 1 | 42 |
| *Vertigo antivertigo* (Draparnaud) | 29 | – |
| *V. pygmaea* (Draparnaud) | 4 | 63 |
| *Pupilla muscorum* (Linné) | 1 | 32 |
| *Lauria cylindracea* (da Costa) | – | 1 |
| *Acanthinula aculeata* (Müller) | – | 34 |
| *Vallonia costata* (Müller) | 1 | 1 |
| *V. pulchella* (Müller) | 15 | – |
| *V. excentrica* Sterki | – | 440 |
| *Ena obscura* (Müller) | – | 9 |
| *Clausilia bidentata* (Ström) | 7 {mainly apices | 28 |
| *Cecilioides acicula* (Müller) | – | 176 |

| | Bowleaze | Blashenwell |
|---|---|---|
| *Vortex lapicida* (Linné) | – | 5 |
| *Arianta arbustorum* (Linné) | 1 | – |
| *Helix nemoralis* Linné | Fgts. | 15 |
| *H. aspersa* Müller | 2 | 43 |
| *Hygromia striolata* (Pfeiffer) | – | 114 |
| *H. hispida* (Linné) | 9 + a few small examples | 153 |
| *Monacha granulata* (Alder) | 28 | – |
| *Helicella virgata* (da Costa) | – | 94 |
| *Punctum pygmaeum* (Draparnaud) | 1 | 56 |
| *Discus rotundatus* (Müller) | – | 162 |
| *Arion* sp. (granules) | A | C |
| *Vitrea crystallina* (Müller) | – | 29 |
| *Oxychilus cellarius* (Müller) | – | 8 |
| *Zonitoides nitidus* (Müller) | 1 | – |
| *Retinella radiatula* (Alder) | – | 1 |
| *R. nitidula* (Draparnaud) | – | 106 |
| *R. pura* (Alder) | – | 1 |
| *Vitrina pellucida* (Müller) | – | 1 |
| *Limax* sp. | 40 | – |
| *Pisidium* sp. | 1 valve | – |
| *Patella vulgata* Linné | 9 | – |
| *Littorina littorea* (Linné) | 9 | – |
| *Buccinum undatum* Linné | – | x |
| *Ostrea edulis* Linné | 4 valves | x |
| *Cardium edule* Linné | 8 „ | x |
| [Tapes] *Paphia* cf. *decussata* (Linné) | 2 „ | – |
| ANGIOSPERMAE | | |
| *Vitis vinifera* Linné | 1 seed | – |

A = Abundant. x = Species present in deposit.

The animal bones and marine shells in the Bowleaze occupation layer are, of course, human food-debris; even *Paphia decussata* is edible, and all the marine mollusca live in the district at present. The single grape seed may be evidence of vines having grown at Bowleaze in Roman times, but it may possibly have been introduced into the deposit at a later time. In Mr. Davis' opinion the non-marine molluscan assemblage suggests the former presence of scrubland, with moss, dead leaves and grass, among which many species could live. Most probably the lower ground was damp and marshy, and adjoined the bank of a slow and muddy stream. The rainfall appears to have been greater than at present. The deposit is not truly fluviatile, although it has yielded a few aquatic species of mollusca. Occupation by a Romano-British people appears to have taken place here mainly in the fourth century A.D., at a site on which rubbish from a previous human occupation in the second century still remained. Although some of the remains of edible molluscs and mammals may be food-debris of the second century, it is evident that the majority, at least, represent marine mollusca gathered from the shore in the vicinity, and domestic animals kept by the Romano-British community, during the fourth century.

(h) **The Holocene brown loam in the beach at the eastern end of the cove.** This deposit is a brown argillaceous loam with scattered Quaternary shells. Washed residues contain colourless quartz grains (mostly well-rounded); a fair proportion of sandstone and ooliths; scattered subangular fragments of flint or chert; some oolite fragments; small spherical ironstone nodules and Jurassic shell-fragments, whilst a probable test of *Ammobaculites* sp. was noted. The loam has been seen only at one point, at the back of the beach on the eastern side of the cove, from about 142 yds. to about 148 yds. east of the Jordan stream. Although not seen in the cliff, it may have been hidden by material slipped from above. Its observed extent from the foot of the cliff toward the sea was at least six feet but its margins were obscured by beach material. Its thickness is unknown since this could only be determined by digging a pit in the beach, which was impracticable in the time available for examining the site. The deposit was reasonably free from shingle during the writer's visit in October 1953, but must normally be covered by beach material. Samples of the loam collected by the author were washed by Mr. Davis, who obtained from them the following nineteen species of mollusca, as determined by him.

## FAUNAL LIST FOR THE BROWN LOAM IN THE BEACH AT THE EASTERN END OF THE COVE

| MOLLUSCA | |
|---|---|
| *Valvata piscinalis* (Müller) | 1 |
| *Pomatias elegans* (Müller) | Fgts. |
| *Carychium minimum* Müller | 6 |
| *Succinea putris* (Linné) | 1 |
| *Vertigo pygmaea* (Draparnaud) | 2 |
| *Pupilla muscorum* (Linné) | 3 |
| *Vallonia costata* (Müller) | 9 |
| *V. excentrica* Sterki | 15 |
| *Balea perversa* (Linné) | 1 |
| *Cecilioides acicula* (Müller) | 4 |
| *Helix nemoralis* Linné | Fgts. |
| *H. aspersa* Müller | 1 + fgts. |
| *Helicella virgata* (da Costa) | 10 |
| *H. itala* (Linné) | 4 |
| *Punctum pygmaeum* (Draparnaud) | 1 |
| *Discus rotundatus* (Müller) | 1 |
| *Arion* sp. (granules) | A |
| *Vitrea crystallina* (Müller) | 2 |
| *Limax* sp. | 5 |

Fgts. = fragments.

The only known Quaternary deposit at Bowleaze resembling this loam at all closely is the greyish-brown alluvial loam seen in Excavation III in the beach, on the east bank of the Jordan. They are both similarly coloured argillaceous loams with scattered shells, but a comparison of washed residues shows that the alluvial loam differs from the present deposit in containing abundant fragments of sandstone and carbonised wood, while ooliths are rare. Fragmentary shells of *Patella*, *Littorina* and *Paphia* occur, but have not been found in the loam now under consideration. A comparison of the non-marine molluscan faunas of the two deposits shows that they are distinct, but the fauna of the present loam resembles those of the tufaceous loam at Bowleaze and the Romano-British layer at Blashenwell, although it is identical with neither.

The constituents of this loam appear to show that it was formed principally from the debris of Corallian Beds; particularly from clays and sandstones of this age, in the neighbourhood. Its position at the foot of the present cliff shows that it must be later than that feature, the existing face of which cannot be older than Historic times. Mr. Davis, from his examination of the mollusca, finds that they constitute a terrestrial fauna with one freshwater species, *Valvata piscinalis*, and regards the assemblage as indicating former grassland invaded by scrub, with a trickle of water present. The deposit is thus seen to be not alluvium, but probably a rainwash accumulated on sloping ground where a streamlet allowed *Valvata* to live. A destruction of the grassland and scrub, with their associated mollusca, probably occurred during, or immediately before, the formation of the loam, which latter appears to have taken place in Roman or post-Roman times, as judged by the position of the deposit in relation to the present cliff-face and the character of its molluscan fauna. It is possible that the brown loam is the rainwash from under which the elephant remains recorded by Strahan (1898) were obtained (Carreck, 1955, p. 172).

(i) **The Holocene yellow loam with limestone and sandstone debris.** This is a poorly-bedded yellowish loam containing subangular pieces of limestone (mostly oolitic) and sandstone, with many obvious ooliths and scattered shells of Quaternary non-marine mollusca. Examination of washed residues shows abundant angular to subangular pieces of oolite and sandstone; a fair proportion of ooliths; angular fragments of calcite crystals; a few quartz pebbles and scattered angular shell-fragments of Jurassic age. The deposit directly overlies the Corallian rocks at one point, and the bluish-grey loam with *Ammobaculites* at another (as shown in Fig. 2), and directly underlies the deposit here believed to be Damon's Loam, in the cliff on the eastern side of the cove, having been observed from about 112 to about 133 yds. east of the Jordan stream. Its base rises from 4 ft. 1 in. to 8 ft. 2 in., and its surface from 8 ft. 1 in. to 9 ft., above the beach between 120 and 133 yds. east of the Jordan, giving a maximum observed thickness of 4 ft. at the first point. The deposit may well continue eastwards along the cliff beyond the recorded distance of about 133 yds. east of the stream, after which the cliff is badly masked by talus. The loam appears to be banked against the Corallian rocks which form the eastern side of the Jordan Valley here, as in the case of the bluish-grey loam with *Ammobaculites* mentioned previously.

From samples collected by the writer, Mr. Davis isolated sixteen species of non-marine mollusca, which he has determined as follows:

### FAUNAL LIST FOR THE HOLOCENE YELLOW LOAM WITH LIMESTONE AND SANDSTONE DEBRIS

| | |
|---|---|
| *Carychium minimum* Müller | 1 |
| *Lymnaea peregra* (Müller) | 5 |
| *Ancylus fluviatilis* Müller | 2 |
| *Succinea putris* (Linné) | 2 |
| *Vertigo pygmaea* (Draparnaud) | 1 |
| *Vallonia costata* (Müller) | 1 |
| *V. excentrica* Sterki | 8 |
| *Cecilioides acicula* (Müller) | 3 |
| *Helix nemoralis* Linné | 1 |
| *Hygromia hispida* (Linné) | 1 |
| *Helicella virgata* (da Costa) | 2 |
| *H. itala* (Linné) | 1 |
| *Punctum pygmaeum* (Draparnaud) | 1 |
| *Arion* sp. (granules) | Very rare |
| *Retinella radiatula* (Alder) | 1 |
| *Pisidium amnicum* (Müller) | 1 valve |

Microscopic examination of a washed residue from this deposit showed one small piece of red brick, tile or pottery, lying among the normal constituents. The deposit, when seen in the field, closely resembled the bluish-grey loam with sandstone debris described above, as regards structure, but differed in colour and in containing many ooliths easily seen on its weathered surface, while, as already stated, the bluish-grey loam yielded no Quaternary fossils of any kind. The yellow loam resembles still more closely the Early Holocene loam on the western side of the cove, both in structure and colour, and at an early stage of the present investigation it was considered possible that the two deposits might be identical, but a comparison of their molluscan faunas shows them to be entirely distinct. Again, although the yellow loam bears some superficial resemblance to the Late Pleistocene Head and Loam at Portland Bill, the molluscan faunas of the two deposits are not comparable (Kennard & Woodward, 1901, pp. 246, 258–60). On comparing the molluscan assemblage of the yellow loam with those of the remaining deposits already mentioned (pp. 80, 84, 87, 89), it is found that it most nearly resembles those of the Spring Bottom grey tufa, the Bowleaze tufaceous loam, and the Romano-British layer at Blashenwell, with only slightly less resemblance to those of the brown loam in the eastern beach and the Early Holocene loam, at Bowleaze. Mr. Davis' study of the molluscan fauna of the yellow loam leads him to the conclusion that this assemblage, of three freshwater and thirteen terrestrial species, most probably indicates former grassland with a little scrub and a trickle of fresh water. The grassland and scrub must have been destroyed in a similar manner to that presumed to have existed just prior to, or during, the formation of the brown loam in the beach at the eastern end of the cove.

From a consideration of all the evidence given above, it may be seen that the yellow loam is composed of detritus of Jurassic (apparently Corallian) rocks in the neighbourhood. It is not a truly fluviatile deposit, particularly in view of the rarity of water-worn constituents, and is evidently a sludge, or hill-wash. The fragment of ceramic material noted above may have been introduced into it after its deposition, but if not, would show that the deposit could not be older than early Historic times, and this possibility is apparently supported by the molluscan evidence, since its fauna corresponds most closely with three deposits of approximately Iron Age to Roman times, the Spring Bottom grey tufa, the Bowleaze tufaceous loam and the Romano-British layer at Blashenwell.

(j) **Deposit believed to be Damon's Loam.** In 1864 Damon described a deposit on the east side of Bowleaze Cove as follows. 'On the slopes of the valley at Preston, which terminates on the coast, there is a drift deposit of yellow loam, containing numerous land-shells of existing species, and in addition, marine species of kinds that are still being lodged on the adjacent shore. A section of the above deposit, which rests on the Calcareous grit of the Coral rag, may be very clearly seen in the cliff, as it rises on the east side of the valley to a height of from ten to twelve feet above high-water mark.' This description was repeated by him without amplification, in 1884. The cliff on the east side of the cove appears to show only two deposits that could possibly correspond with Damon's description, the yellow loam with limestone and sandstone debris described above, and another loam, occurring in the upper part of the cliff. It appears improbable that the former could be Damon's Loam, since no traces of marine shells have been found in it by the present writer, and it has only been seen by the latter from about 12 to 13 ft. above high-water mark, although it may well continue behind the cliff-talus to a lower level. The second deposit possibly identical with Damon's Loam is a rather structureless brown argillaceous loam with few obvious stones. Examination of washed residues showed the presence of many fragments of whitish sandstone; a fair proportion of oolite fragments; ooliths and very small race nodules; infrequent rounded quartz grains and Jurassic shell-fragments; some minute spherical ironstone nodules; an equally small pyrites nodule; some subangular pieces of flint or chert; rare fragments of carbonised wood and Quaternary shell fragments. Non-marine molluscan shells were infrequent in the deposit. Two shells of *Littorina* were obtained from it and one medium-sized beach pebble was found imbedded in its vertical face. The deposit has been seen to a maximum thickness of 4 ft., rests directly on the yellow loam with limestone and sandstone debris already described, and is overlain only by soil and turf. It is seen in the cliff from about 112 yds. to about 133 yds. east of the Jordan stream, whilst its base rises from about 8 to 9 ft., and its surface from about 12 to 13 ft., above beach level. Together with the Holocene yellow loam, and the bluish-grey loam with *Ammobaculites*, it appears to be banked against the Corallian Beds which form the eastern side of the valley at this locality. From samples of the loam collected by the present writer, Mr. Davis obtained the following sixteen species of non-marine mollusca, listed below:

## FAUNAL LIST FOR THE DEPOSIT BELIEVED TO BE DAMON'S LOAM

| | |
|---|---|
| *Pomatias elegans* (Müller) | Fgts. |
| *Carychium minimum* Müller | 2 |
| *Lymnaea truncatula* (Müller) | 2 |
| *Succinea putris* (Linné) | 3 |
| *Vallonia excentrica* Sterki | 2 |
| *Clausilia bidentata* (Ström) | 1 |
| *Cecilioides acicula* (Müller) | 1 |
| *Helix nemoralis* Linné | 2 + fgts. |
| *H. aspersa* Müller | Fgts. |
| *Hygromia hispida* (Linné) | 2 |
| *Helicella virgata* (da Costa) | 3 |
| *Discus rotundatus* (Müller) | 2 |
| *Arion* sp. (granules) | C |
| *Vitrea crystallina* (Müller) | 1 |
| *Retinella nitidula* (Draparnaud) | 1 |
| *Limax* sp. | 2 |
| *Littorina littorea* (Linné) | 2 |

Fgts. = fragments.

The only object of possible archaeological significance found in the deposit is a flint flake about an inch in length, bearing a whitish patina. This appears to be a waste flake struck by man, but may be due to natural causes, and even if of human fabrication, could be of any age from about Mesolithic to Saxon. Lithologically the loam is not comparable with any other Quaternary deposit in the cove; its non-marine molluscan assemblage compares most closely with that of the Bowleaze tufaceous loam, but the two faunas are not identical. Mr. Davis regards the molluscan assemblage of the present loam as indicative of scrubland, with damp patches for *Lymnaea truncatula* and *Succinea putris*. These two species do not indicate running water, since neither is truly aquatic, and the whole fauna is therefore of a terrestrial nature. As in the case of the Holocene yellow loam, and the brown loam in the eastern beach, the scrubland believed to have existed immediately before or during the time of accumulation of this loam must have been destroyed by the formation of the deposit. The available evidence shows that the loam is composed essentially of material derived from Jurassic (probably Corallian) sandstones and limestones, the detritus presumably having come from the higher ground in the vicinity. The two shells of *Littorina* may perhaps have been carried up from the adjacent shore, in the past, by birds such as gulls, or oyster catchers (*Haematopus*), but may be human food-debris from a kitchen midden accumulation of Romano-British or later date. The beach pebble may have been hurled against the cliff by the waves during recent rough weather. The possibly humanly-struck flint flake is of little significance. The palaeontological features common to both the Bowleaze tufaceous loam and the present brown loam may indicate an Iron Age to Roman date for the latter deposit, but the evidence is quite insufficient for further conclusions to be drawn. The composition and depositional features of this loam, together with the molluscan evidence, make it probable that the deposit is a rainwash, and it may well be of Early Historic date. Whether this deposit is Damon's Loam cannot be satisfactorily decided in the absence of any sufficiently detailed description of the latter by him, particularly the lack of a faunal list. Further, the present loam cannot be reasonably described as yellow, although Damon's adjective may have been loosely applied. Therefore, although the brown loam appears to be very probably identical with Damon's Loam, it is impossible to be certain.

(k) **The Holocene alluvium of the Jordan.** The only previous reference to the alluvium at this locality is by Arkell (1947, p. 350), as noted above. His 'dark alluvial clay' and 'recent stream gravel' could not be identified with certainty by the present author in 1951–2, but a series of alluvial beds was studied by the latter, as described below. The positions of the following excavations have been stated already, and all faunal lists for the alluvial beds are given later.

## STRATIGRAPHIC SEQUENCES

*Excavation I.* The height of the section, from water level to the turf above, was 27 in.

| | |
|---|---|
| Turf | |
| Soil ... ... ... ... ... ... ... ... ... | 4 in. |
| *Bed v* | |
| Buff-coloured argillaceous sand, full of small mollusca (mainly *Potamopyrgus*) and caddis cases (*Sericostoma*). Irregular or impersistent ... ... ... ... ... | 2 in. |
| *Bed iv* | |
| Fairly dark clay with sandy seams ... ... ... ... | 9 in. |

*Bed iii*
Dark clay, with frequent carbonised wood and orange limonitic streaks. A few fragmentary leaves at top ... 6½ in.
*Bed ii*
Ill-graded coarse sand and gravel, blue and argillaceous in its lower part ... ... ... ... ... ... ... 11 in.
*Bed i*
Sandy and gravelly blue clay, with scattered shells and fragments of carbonised wood ... ... Penetrated 3–4 in.

*Excavation IA.* Here a blue stony clay was seen from water level upwards to a height of about 10 in., containing a few scattered shells and an indeterminate piece of bone. The clay passed upward into light brown loam with ferruginous streaks, apparently unfossiliferous, and about 3½ ft. in thickness. Access to the section was very difficult, as a result of which only one mollusc and the bone fragment were collected.

*Excavation II.* The height of this section from water level to the turf above was 30 in.

Turf
Soil ... ... ... ... ... ... ... ... ... 4 in.
passing down into:
*Bed iii*
Brownish-grey loam with ferruginous streaks or patches, and containing scattered shells and plant-debris ... ... 17 in.
passing down into:
*Bed ii*
Blue clay with scattered shells and plant-remains ... ... 12½ in.
resting on:
*Bed i*
Fine gravel ... ... ... ... ... Penetrated 2–3 in.

*Excavation III.* This section showed only one deposit, seen to 1 ft. 6 in. from water level. The deposit formed the surface of the beach where all shingle had been removed by the sea during rough weather. It was a greyish-brown argillaceous loam with scattered shells and a few subangular pieces of flint; its extent below water level was uncertain. A washed residue consisted of abundant carbonised wood; Quaternary shell-fragments and pieces of sandstone; scattered angular and subangular pieces of flint or chert; infrequent subangular fragments of quartz, rare ooliths and a tubular race nodule.

The loam extended southwards along the bank of the stream for a few yards until it was obscured by shingle, and northwards along the bank for about 7½ yds. until it was rather abruptly replaced in the same direction and at the same level by a very peaty argillaceous loam, dark grey in colour, mottled with hydrated ferric oxide and containing scattered shells of

## FAUNAL AND FLORAL LISTS FOR THE HOLOCENE ALLUVIUM

x=Species present in deposit.
A=Abundant. C=Common. S=Scarce.

| | Excavation I | | | | | Exc. IA | Excavation II | | | Exc. III |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bed i | Bed ii | Junction of Beds ii & iii | Bed iii | Bed v | Blue stony clay | Bed ii | Junction of Beds ii & iii | Bed iii | Greyish-brown loam |
| CHORDATA | | | | | | | | | | |
| '*Microtus*' sp. Left femur | | | | | | | x | | | |
| *Ovis* or *Capra*. Lumbar vertebra | | | x | | | | | | | |
| *Rana* sp. Limb bones | | | | | 1 | | | 1 | | |
| *Acerina* cf. *cernua* (Linné) Sagitta otolith of Percoid fish | | | | | | | | x | | |
| INSECTA. COLEOPTERA | | | | | | | | | | |
| *Elmis maugei* Bedel var. *aeneus* (Mueller) Pronotum | | | | | x | | | | | |
| *Calandra granaria* Linné Both elytra, and meso-scutellum | | | | | | | | | x | |
| *Donacia* sp. Two elytra | | | | | x | | | | | |
| *Cercyon* (*Cerycon*) *analis* Paykull Left elytron | | | | | | | | | x | |
| *Gyrinus* sp. Right elytron | | | | | x | | | | | |
| *Pterostichus* sp. Head | | | | | x | | | | | |
| *Clivina collaris* (Herbst). Prothorax | | | | | | | x | | | |
| *Nebria brevicollis* (Fabricius) Part of left elytron | | | | | | | x | | | |
| INSECTA. TRICHOPTERA | | | | | | | | | | |
| *Sericostoma personatum* Spence. Larval and pupal cases | | | | | A | | | | | |
| OSTRACODA | | | | | | | | | | |
| *Candona candida* (O. F. Müller). Valves | | | | | C | | C | | C | |
| *Herpetocypris reptans* (Baird) Valves | | | | | S | | S | | S | |
| MOLLUSCA | | | | | | | | | | |
| *Valvata piscinalis* (Müller) | 1 | | | 6 | 30 | | 2 | 16 | 6 | 15 |
| *Pomatias elegans* (Müller) | | | | | | | | 1 | | |
| *Potamopyrgus jenkinsi* (E. A. Smith) | 2 | | | C | A | | | 1 | | |
| *Carychium minimum* Müller | | | | 1 | 2 | | 8 | 32 | 6 | 30 |
| *Lymnaea truncatula* (Müller) | | | | | 3 | | 3 | 13 | 4 | |
| *L. palustris* (Müller) | | | | 1 | 11 | | | 3 | | 3 |
| *L. peregra* (Müller) | | | | 3 | C | | | 1 | 2 | 18 |

FAUNAL AND FLORAL LISTS FOR THE HOLOCENE ALLUVIUM—*cont.*

x=Species present in deposit.
A=Abundant. C=Common. S=Scarce.

| | Excavation I | | | | | Exc. IA | Excavation II | | | Exc. III |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bed i | Bed ii | Junction of Beds ii & iii | Bed iii | Bed v | Blue stony clay | Bed ii | Junction of Beds ii & iii | Bed iii | Greyish-brown loam |
| MOLLUSCA—*cont.* | | | | | | | | | | |
| *Physa fontinalis* (Linné) | | | | | 12 | | | | | |
| *Planorbis vortex* (Linné) | | | | | 19 | | | | | |
| *P. leucostoma* Millet | | | | | 4 | | | | | |
| *P. albus* Müller | | | | | 8 | | | 7 | 4 | 10 |
| *P. crista* (Linné) | | | | | 3 | | 4 | 3 | | |
| *P. contortus* (Linné) | | | | | 24 | | 1 | 1 | | |
| *Ancylus fluviatilis* Müller | | | | C | C | | 4 | 6 | 2 | 8 |
| *Succinea putris* (Linné) | | | | | C | | | 13 | 3 | 1 |
| *Cochlicopa lubrica* (Müller) | | | | | 20 | | 3 | 13 | 2 | 8 |
| *Vertigo antivertigo* (Draparnaud) | | | | | 9 | | | | | |
| *V. pygmaea* (Draparnaud) | | | | | | | | 3 | | 4 |
| *Lauria cylindracea* (da Costa) | | | | | 3 | | | | | 1 |
| *Vallonia costata* (Müller) | | | | | 2 | | | | | 4 |
| *V. pulchella* (Müller) | 1 | | | 2 | 2 | | 2 | 18 | 8 | |
| *V. excentrica* Sterki | | | | | | | | | | 3 |
| *Clausilia bidentata* (Ström) | | | | | 1 | | | 3 | | |
| *Cecilioides acicula* (Müller) | | | | 1 | 4 | | | | | |
| *Helix nemoralis* Linné | | | | | | | | | 2 | |
| *H. aspersa* Müller | | | | | | 1 | | | | 1 + fgts. |
| *Hygromia striolata* (C. Pfeiffer) | | | | | 3 | | | | | |
| *H. hispida* (Linné) | 4 | | | 3 | 18 | | 4 | 29 | 7 | 22 |
| *Monacha granulata* (Alder) | | | | | 5 | | | 1 | | 1 |
| *Punctum pygmaeum* (Draparnaud) | | | | | | | | 1 | | |
| *Discus rotundatus* (Müller) | 1 | | | | 12 | | 1 | 11 | 3 | 1 |
| *Arion* sp. (granules) | | | | 2 | 3 | | 2 | A | 20 | C |
| *Vitrea crystallina* (Müller) | 1 | | | | 12 | | 1 | 5 | 1 | 4 |
| *Oxychilus cellarius* (Müller) | | | | | 2 | | | 3 | | 2 |
| *Retinella* sp. indet. | | | | | | | 1 | 2 | 1 | |
| *R. nitidula* (Draparnaud) | | | | | 4 | | | 3 | | 1 |
| *Zonitoides nitidus* (Müller) | | | | | 2 | | | | | 1 |
| *Limax* spp. | | | | 2 | 1 | | 2 | 7 | 3 | 2 |
| *Sphaerium corneum* (Linné) | | | | | | | 3 | | 3 | |
| *Pisidium* spp. | | | | C | C | | C | C | 3 | |
| *P. amnicum* (Müller) | 2 | | | 1 | | | 2 | 15 | 1 | 4 |
| *P. casertanum* (Poli) | | | | | | | | | | 5 |
| *Patella* sp. | | | | | | | | | | fgts. |
| *Littorina* sp. | | | | | | | | | | fgts. |
| *Cardium* sp. Rolled fragment of valve | | x | | | | | | | | |
| [*Tapes*] *Paphia* sp. | | | | | | | | | | fgts. |
| ANGIOSPERMAE | | | | | | | | | | |
| *Prunus spinosa* Linné Endocarp of Sloe (Blackthorn) | | | | | x | | | | | |

non-marine mollusca. A fragmentary mandible and part of a maxilla of a lamb (*Ovis*) or kid (*Capra*) was found in this peaty deposit. The latter continued northwards, in the stream bank, for at least 7¼ yds., beyond which it was hidden by vegetation. No deposits other than modern beach shingle were seen at any point in the beach on the opposite bank of the stream.

The organic remains obtained from the alluvium in the four excavations are as follows; the determinations of the non-marine mollusca and notes upon them are by Mr. Davis, who also recorded the marine shells from Excavation III.

The fragment of *Cardium* valve found in Bed ii of Excavation I was associated with three rolled Romano-British potsherds and more probably represents human food-debris of that date than the result of salt water entering the mouth of the river during the accumulation of the deposit. Mr. Farrar has reported upon these sherds as follows. 'One can say little more than that these are Romano-British. The only piece of recognisable form, part of the rim of a cavetto-rimmed cooking pot, is too small for precise determination, but is probably later than the first century A.D. I would say it could be anything from second to fourth century.' The fragments of marine shells in the greyish-brown loam of Excavation III are also most probably food-waste from a site of human occupation, Romano-British or later in date. One or two fragments of red brick or tile were found in Bed i of Excavation I, and a larger piece at the junction of Beds ii and iii of Excavation II. Insufficient time made it impracticable to search for mollusca in Bed ii, at the junction of Beds ii and iii, and in Bed iv, of Excavation I, and in Bed i of Excavation II.

From the evidence of the non-marine mollusca Mr. Davis suggests the following conclusions. *Excavation I.* In Bed i the mollusca indicate flooding of a land-surface, in Bed iii stream- and flood-debris is present, and in Bed v such debris is again present, but at the time of deposition the stream-water was probably fresher. *Excavation II.* In Bed ii stream and flood debris occurs, at the junction of Beds ii and iii flooded and marshy ground is indicated, and the mollusca of Bed iii also point to a flooded land-surface. *Excavation III.* In the greyish-brown loam the molluscan assemblage indicates a stream, probably not quickly-flowing, but subject to flooding, since the deposit contains abundant sweepings of the land. The sites represented in the deposits of all three excavations, therefore, appear to have been generally much damper than at present. The Coleoptera comprise three aquatic and five terrestrial forms, representing part of the stream-fauna and sweepings of the damp stream-margins. The Corn Weevil, *Calandra granaria* L., is noteworthy, as it infests granaries where the larvae do much damage to stored corn. A comparison of the molluscan assemblage of the greyish-brown loam of Excavation III with those of the other beds of alluvium described above, has shown that this deposit is almost certainly to be correlated with the similar loam forming Bed iii in Excavation II, but the presumed lateral connection of the two loams has not been traced, owing to a mantle of vegetation obscuring the stream-banks between them. No correlations between any of the other alluvial beds have been established so far. All the deposits in Excavations I, IA, II and III are clearly of alluvial origin, as judged by their relation to the present stream, their well-bedded character, and particularly by the composition of their molluscan faunas. Little evidence for dating purposes is yet available from the sections of alluvium examined by the author, but there is nothing to suggest that any of the beds is older than the Roman period, although deposits below the base of the present sections may date back to Early Holocene times.

In the lowest portion of the cliff on the eastern side of the cove, from about 65 yds. to about 76 yds. east of the Jordan stream, a grey argillaceous loam was seen in 1954 to a thickness of two feet. It contained limestone and chert pebbles, subangular pieces of flint and fragments of wood, but appears to have been contaminated in recent times. Its eastern edge is covered by concrete, as shown in Fig. 2. It is probably alluvium, but is of no special significance.

## 3. CONCLUSION

The evidence recorded in this paper gives some impressions of the sequence of molluscan and other life in the Bowleaze area in later Quaternary times, and some deductions have been made regarding the probable biotopes formerly existing at this locality. Little work of this kind has been carried out previously in the Weymouth district.

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# The Deposition of the Upper Dalradian Rocks of the Banffshire Coast

by JOHN SUTTON and JANET WATSON

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**ABSTRACT:** Sedimentation structures in Upper Dalradian rocks belonging to the Banff Division of north-east Scotland suggest that the rocks were deposited in deep water by the action of turbidity currents. These structures, including grading of grits, greywackes and flags, and slumping, are described in detail and compared with the structures of sediments in other series of greywacke-facies. It is suggested that the change of sedimentary facies at the beginning of Upper Dalradian times may have been due to the emergence of a new land-mass on the north-western side of the basin of deposition, providing a rapid supply of coarse detritus. The uplifting of this land-mass might have been associated with an early phase of Caledonian folding and metamorphism.

## 1. INTRODUCTION

A MAGNIFICENT section across the Dalradian Series of north-east Scotland is to be found along the southern shore of the Moray Firth. It provides the best opportunity for the study of a group of rocks which is otherwise poorly-exposed in this part of the country. The oldest Dalradian rocks appear in the west, where alternations of quartzite, siliceous granulite, black schist, mica schist and limestone make up the Keith Division of Read (1923, p. 11). The eastern part of the section is occupied by rocks of rather different types, alternations of metamorphosed grits, greywackes, slates and calcareous rocks making the Banff Division of Read.

The members of the Keith Division extend south-south-westward through Perthshire into the south-west Highlands. The Banff Division with which this paper is concerned, on the other hand, is confined to the north-east Lowlands. It is structurally higher than the Keith Division, and appears to form the youngest part of the Dalradian succession of north-east Scotland. It is, therefore, probably in some measure stratigraphically equivalent to the grits, greywackes and slates forming the younger part of the Dalradian along the Highland Border and in the Loch Awe district, although no direct connection with these districts can be established.

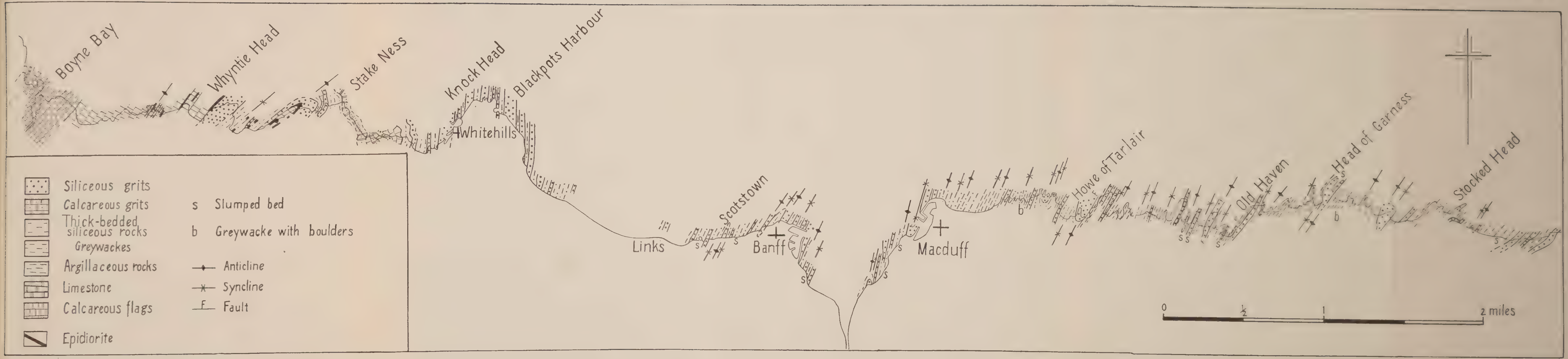
The early work on the metamorphic rocks of Banffshire is summarised in the Geological Survey Memoir, 'The geology of the country round Banff, Huntly and Turriff'. This Memoir (Read, 1923) covers the country shown on Sheets 86 and 96 of the 1-inch Geological Survey Map of Scotland; its publication followed a thorough revision by Read of the original survey by J. Horne and J. S. G. Wilson, which had led to the appearance of the first edition of Sheet 96 in 1895.

Read established the two divisions of the Dalradian and deduced in each a stratigraphical succession (1923, p. 56) which was subsequently confirmed by the evidence of sedimentary structures (Read, 1936). The relations of the Keith and Banff Divisions remain obscure. Read pointed out that the two divisions differed both in original lithology and in metamorphic state, and that their line of junction was marked by a number of structural anomalies. He suggested that this line of junction ('the Boyne Line') might be a movement-plane, or slide, along which different members of the two divisions had been brought into contact.

The Boyne Line was folded in movements which are known to have occurred before the final metamorphism of the Banff Division, from which it follows that any sliding that took place along it must have been pre-metamorphic. Garnet, kyanite or sillimanite are the characteristic minerals of pelitic rocks of the Keith Division, and in some localities permeation by quartzo-felspathic material has taken place.

The pelitic rocks of the Banff Division show signs of two metamorphic episodes. In the first of these, which occurred when the cleavage was formed, and appears to be syntectonic, chlorite and biotite developed. In the second episode, which was post-tectonic, andalusite, staurolite and cordierite were formed on a regional scale. Sillimanite is present in certain of the lowest members of the Banff Division, immediately in contact with the underlying Keith Division. It is not clear to which phase of metamorphism this mineral is to be attributed.

In 1951 we noticed slump beds, and other signs of submarine disturbance, in the Banff Division and in the summer of 1953 we returned to map in


Boyne Bay
Whyntie Head
Stake Ness
Knock Head
Blackpots Harbour
Whitehills
Links
Scotstown
Banff
Macduff
Howe of Tarlair
Old Haven
Head of Garness
Stocked Head
Siliceous grits
Calcareous grits
Thick-bedded siliceous rocks
Greywackes
Argillaceous rocks
Limestone
Calcareous flags
Epidiorite
s Slumped bed
b Greywacke with boulders
Anticline
Syncline
F Fault
0
½
1
2 miles

detail the coast-section between Boyne Bay and Gamrie, which lies two miles east of Stocked Head, the easternmost locality shown on Plate 3. Slumping at Banff had been described in an unpublished thesis by R. Walls in 1937.

Many of the sedimentation-structures of the grits, greywackes and flags of the Banff Division are of the kind attributed to the action of submarine turbidity currents. The work of Kuenen, in particular, has shown that a study of these structures may help to elucidate not only the palæogeography of a region, but also its tectonics. In Banffshire it is possible that such a study may throw light not only on the lithological differences but also on the divergent histories of the greywackes of the Upper Dalradian on the one hand and of the underlying rocks of the Keith Division on the other. Such questions are discussed in the last part of the present paper, the main purpose of which is to describe the sedimentation-features of the Banff Division rocks of the coast-section. It forms part of a renewed attack on the problems of the Banff Division which is being conducted by Dr. O. C. Farquhar and ourselves, at the suggestion of Professor Read.

## 2. OUTLINE OF THE STRATIGRAPHY

Read recognised four groups in the Banff Division (1923, p. 6; 1936). These are well exposed along the coast, which runs almost at right-angles to the strike and the direction of the fold-axes, and occur in the following order, from west to east, between Boyne Bay and the Gamrie Outlier of Old Red Sandstone (Read, 1923, p. 6; 1936).

*Boyne Limestone* (oldest): thick limestone and subordinate mica schists and phyllites
*Whitehills Group*: rapid alternations of pebbly grits, pebbly limestones, flags, phyllites, limestones, etc.
*Boyndie Bay Group*: andalusite-schist and pebbly grit
*Macduff Group* (youngest): slate, greywacke and pebbly grit.

Each of the four divisions consists of alternations of a number of sedimentary types and attention may next be drawn to the lithological grouping which we have adopted for the purposes of mapping. In this grouping, rocks of similar original lithology have been placed together and the effects of subsequent metamorphism have been disregarded. Thus, for example, slates, spotted slates and andalusite schists are shown with the same ornament on Plate 3, since all are derived from argillaceous rocks. The lithological types recognised are as follows:

(a) Siliceous grits
    (i) Pebbly grits
    (ii) Pebbly grits with mudstone fragments
    (iii) Slumped pebbly grits
(b) Calcareous grits

(c) Thick-bedded siliceous rocks other than grits
    (i) Undisturbed
    (ii) Slumped
(d) Thin-bedded greywackes, generally with good graded bedding
    (i) Undisturbed
    (ii) Slumped
(e) Shales
(f) Alternating greywackes and shales with local thin limestones
(g) Alternating siliceous and calcareous flags with shales
(h) Limestones.

Read (1923, pp. 49–61) has already described the variations to be seen along the coast-section, and these variations, shown in detail on Plate 3, are summarised in Table I. We have determined the attitude of the beds and established the nature of the folds, wherever the rocks are exposed east of Stake Ness. With this information it has been possible to obtain estimates of the thicknesses of the different parts of the succession and to put forward more detailed accounts of the stratigraphical sequence within each of the groups which compose the Banff Division. To the west of Stake Ness satisfactory indications of the 'way-up' of beds are rare, small-scale folding is common and exposures are not always satisfactory. As a result, the estimates of thickness of the Boyne Limestone, and the calcareous part of the succeeding Whitehills Group, are the least reliable of those shown in Table I.

Table I brings out the importance of grits and greywackes in the Banff Division. Slates are not the predominant member of the Division, as has been assumed in the past, for the great width of the slate outcrop is the result of repeated small-scale folding of these incompetent beds. The thicker sequences of massive beds are not folded in this manner. Once this is appreciated, it becomes clear that the Banff Division, with its richness in grits and greywackes, must be more like the Upper Dalradian rocks to the south-east than the present small-scale maps (which show the Banff Division as argillaceous) might suggest. The sequence of rocks shown in Table I appears to be over 13,000 ft. in thickness, and illustrates three different types of sedimentation. At the bottom is the Boyne Limestone, made up largely of carbonates with subsidiary non-calcareous intercalations, and apparently formed from calcareous muds with very little detritus. The limestone passes upward through a sequence of calcareous grits and thin limestones into the lower part of the Whitehills Group, which marks the second phase of deposition. During this phase, alternations of calcareous grits, siliceous and calcareous flags, argillaceous rocks and thin limestones were deposited; they represent a stage when detritus, largely unsorted, was brought into an area where calcareous material was still accumulating. Siliceous grits appear for the first time near the top of this

TABLE I

| | PREDOMINANT ROCK TYPE | SUBSIDIARY ROCK TYPES | THICKNESS FEET | EXPOSED IN THE COAST SECTION |
|---|---|---|---|---|
| MACDUFF GROUP | Greywackes | Slates, grits | 3000 | from Stocked Head to Gamrie Bay |
| | Greywackes | Slates, grits | 1000 | from Tarlair to Stocked Head |
| BOYNDIE BAY GROUP | Greywackes | Slates, andalusite schists, grits | 1500 | from Banff Links to Tarlair |
| WHITEHILLS GROUP | Siliceous grits | Andalusite schists | 4000 | from Whitehills to west Boyndie Bay |
| | Calcareous grits | Siliceous grits, calcareous flags, andalusite schists | 1000 | from Stake Ness to Whitehills |
| | Calcareous flags | Siliceous and calcareous grits, andalusite schists, limestones | 1700 | from east of Boyne Bay to Stake Ness |
| BOYNE LIMESTONE | Limestone | Calcareous flags, mica schists | 1000 | from Old Hythe to east of Boyne Bay |

alternating series, at Whyntie Head and Stake Ness. The third phase of deposition was ushered in by the formation of a succession of siliceous grits, 4000 ft. in thickness, which forms the upper part of the Whitehills Group and is exposed at Knock Head. This predominantly gritty series contains subordinate argillaceous rocks and flags; in the succeeding Boyndie Bay and Macduff Groups the proportions are reversed, grits being subordinate to greywackes, flags and shales. The whole succession of rocks, from the siliceous grits of Knock Head upwards, appears to mark a phase in which varying amounts of clastic material were brought into an area where argillaceous, but not calcareous, muds were being deposited.

Table I shows that although the Boyndie Bay and Macduff Groups have a combined width of outcrop of at least seven miles (some of their eastward extension being hidden beneath the Old Red Sandstone), their total thickness (5500 ft.) is not very much greater than that of the grits forming the upper part of the Whitehills Group, the outcrop of which is less than a mile wide. The grits 'young' steadily eastward, whereas the rocks of the Boyndie Bay and Macduff Groups are repeatedly folded.

A comparison of Table I and Plate 3 also brings out the fact that parts of the Boyndie Bay and Macduff Groups appear to be composed of one and the same set of rocks. The junction of the two groups was drawn by Read (1923, p. 60) at a point immediately west of Banff Station, where the andalusite spots characterising the Boyndie Bay Group cease to be visible. In 1936, Read re-emphasised the fact that the boundary marked a metamorphic change and was transitional, thus invalidating Gregory's (1931, pp. 127–9) suggestion that the Macduff Slates rested unconformably upon the Boyndie Bay Group.

Plate 3 shows that the succession of grits, slumped beds and argillaceous rocks occurring to the west of Scotstown is brought back by a complex synclinal fold to form the rocks between Scotstown and Banff Harbour. The rocks on the west limb of the syncline have previously been regarded as part of the Boyndie Bay Group, while the lower rocks of the eastern limb were assigned to the Macduff Group. Thus it appears that the rocks on either side of the boundary are stratigraphically the same, and differ only in their state of metamorphism. These beds, repeated by rapid folding, extend eastwards to the River Deveron, and in all probability continue to form the coast as far east as Tarlair, some two miles from Scotstown. A considerable part of the Macduff Group thus appears to be made up of rocks which are the same age as those forming the top of the Boyndie Bay Group. For this reason it seems best to treat the two groups as parts of a single stratigraphical unit.

The relations of the metamorphic and stratigraphical boundaries near Banff indicate that, although the beds have been folded on a relatively small scale, the metamorphic boundary has not been so folded, since the metamorphism is not symmetrically developed with regard to the folds. Moreover, although there is a general metamorphic increase towards the bottom of the stratigraphical succession, the zones of metamorphism do not follow the bedding in detail, a point made by Walls in 1937. Thus, from Banff Harbour to Scotstown the metamorphism increases stratigraphically upwards. These circumstances confirm Read's view that the metamorphism is post-tectonic.

## 3. SEDIMENTATION STRUCTURES IN THE BANFF DIVISION

(a) **Preliminary remarks.** Although the rocks of the Banff Division are wholly, or partly, recrystallised and are often strongly folded, they have suffered extraordinarily little deformation and frequently the original structures can be made out with as much ease as in an unmetamorphosed series. This fact first became apparent when Read (1936) described graded bedding in many members of the Division, and used the attitude of the structure to determine the order of succession. Wall's recognition of slumping, in 1937, has already been mentioned. In the pages that follow, the types of graded bedding found in the members of the Banff Division are described in detail. An account is given of mudstone-breccias formed within certain graded grit beds, of disturbed rocks which underlie some of the graded beds and of slump sheets in the sequence. In the final section of the paper, the conditions of deposition are considered in the light of these sedimentation-structures.

(b) **Graded beds.** No grading has been found in the Boyne Limestone, which is highly contorted and in which any sedimentary structures would probably have been destroyed. Occasionally graded calcareous grits have been noted in the lower members of the Whitehills Group, but most of these beds are not graded. The siliceous grits which occur between Whyntie Head and Stake Ness, a few hundred feet below the top of the calcareous part of the Whitehills Group, form well-graded beds several feet in thickness; intercalations of rather thinner beds, grading from altered siltstone to altered mud, are common near the level of these grits. The calcareous deposits which follow contain many calcareous grits, which, although not graded, resemble the graded siliceous grits in containing rock fragments and mudstone balls.

The highest part of the Whitehills Group, exposed to the east of that village, consists of a great thickness of siliceous grits, each bed of which is several feet in width. The majority of these beds show simple or interrupted graded bedding, leading from a pebbly base to a fine-grained top. The grits alternate with occasional sequences of thinner beds which are predominantly argillaceous. Many of these are graded, also. Similar types of rock make up the Boyndie Bay and Macduff Groups, though grits do not predominate in the manner that characterises the upper part of the Whitehills Group.

Most of the graded beds seen in this coast-section fall into one of two groups. They are either grits over one foot in thickness, or they are three inches, or less, in thickness and consist of fine-grained greywackes with clay-rich tops. Graded beds ranging in thickness from 3 in. to 12 in., are much rarer. When describing this section, therefore, it is possible to speak of *large-scale* and *small-scale* graded beds.

(i) *Large-scale graded bedding* (*i.e. graded beds over a foot in thickness*)

*General characters.* The coarse grit beds, though often dark when fresh, weather to a light biscuit colour. The pebbles which are visible in the field are, in order of abundance, coarse white quartz, pink and white felspar, opalescent blue quartz and quartzite, with quartz typically forming about 80% of them. The pebbles are commonly ⅛ in. long, though in some beds they reach ¼ in. or ½ in. Very occasionally a bed with pebbles 1 in. to 2 in. in length occurs, and in the Macduff Group, east of Stocked Head, a conglomerate over 20 ft. thick is made up of rounded pebbles, up to 2½ in. across, in a siliceous matrix. The large fragments in the typical pebble-beds are rounded, but the more abundant fragments, less than ¼ in. across, are angular. Most of the pebbles are contained in the lowest few inches, and are particularly abundant in any depressions at the base of a bed. Even this lowest part of the bed is not entirely composed of pebbles; on the contrary, the latter are scattered in a matrix of smaller fragments of varying size. Towards the top of each bed the maximum size of the particles diminishes, and smaller particles make up a progressively larger fraction of the rock. The graded rock with such features is not the result of a clean separation of particles which decrease in size from the bottom to the top, as would be the case in a well-sorted deposit.

The microscope confirms the megascopic evidence of imperfect sorting. In sections of typical grits, the recognisable clastic grains range from 5 mm. to 0.02 mm. in diameter. These grains lie in a recrystallised matrix of quartz, calcite, felspar and micas which is presumed to represent the finest material of the original sediment. The present grain-size and mineral-composition of the matrix depends on the degree of metamorphism to which the rock has been subjected. In the calcareous grits of the Whitehills Group the matrix is composed predominantly of carbonates, with smaller amounts of epidote, amphibole and sphene.

Presumably the large clastic grains of quartz are derived from coarse igneous or migmatitic rocks. Occasionally the fine mosaic of a metamorphosed quartzite, sometimes showing a decided flattening of the grains, can be recognised. A small proportion (two or three in a thin section) of the large quartz grains contain abundant slender rod-like inclusions, up to 0.2 mm. in length. These grains show in hand-specimens an opalescent bluish colour, and seem to be identical with quartz in the pyroxene gneisses from the earliest Lewisian complex (Teall, 1907, p. 54).

Felspars form, at most, a third of the clastic grains, and more often 10–20 % of them. Plagioclase is always dominant and in 50 % of the sections it is the only felspar. Where determinable it appears to be oligoclase, but usually it is much altered. Potash felspar, when present, usually takes the form of fresh microperthite, or microcline. The only other detrital minerals recognised in the sections are muscovite, a few zircons and a single grain of brown tourmaline.

*Thickness of the graded beds.* The thickest graded bed we have found is 15 ft. across, and occurs immediately east of the most easterly houses in Macduff, near the building shown on the 6-in. maps as a cholera hospital; it is graded in the sense that the lower part is richer in pebbles than the upper part. Although this bed is exceptionally thick, beds up to 7 ft. across can be found throughout the succession above the middle of the Whitehills Group, and ten-foot graded beds have been noted at the County Council quarry east of Macduff, and near Banff Gasworks. The origin of such thick graded beds, each presumably the result of a single act of deposition, presents, as Read (1936) pointed out, a considerable problem.

The grits generally occur in series, six to twenty grit beds following one another with little or no intervening material. In any one series there is a certain 'family likeness' marked by some degree of uniformity in the thickness of the beds. Examples of such series were noticed where the thickness ranged from 1 ft. 6 in. to 6 ft. 6 in.; from 2 ft. 5 in. to 7 ft.; from 4 ft. to 6 ft. and from 4 ft. to 8 ft. respectively. The beds above and below a group of grits are often much finer-grained and more thinly-bedded; slates or flags less than 2 in. thick may be found in contact with grits several feet thick, the contact apparently marking a sudden change in the conditions of sedimentation, as exemplified at Scotstown, on the foreshore south-east of Banff, and at Macduff, immediately north-east of the Deveron.

Individual series of grits which are repeated along the coast by folding, like those at Banff and Macduff, can be seen to persist for at least a mile. Inland, Read was able to trace a coarse pebbly quartz-felspar grit for as much as two miles in the Kirkney Water exposures of the Macduff Group (1923, p. 61). On the other hand, individual beds, or series of beds, can sometimes be seen to change in thickness over a distance of a few hundred feet, as in the Howe of Tarlair, where a bed thins from 5 ft. to 1 ft. 3 in. in 110 ft. of its length. In half a dozen localities very coarse ungraded grits, with pebbles more than ½ in. across, appear to form lenticular bands dying out in 100 ft., 130 ft.—or even in 15 ft. It has never been possible to determine the shape of these beds in three dimensions. In the promontory east of the Howe of Tarlair a pebbly bed 5–6 ft. thick dies out in 40 ft. along the strike. Here it can be seen that the bed was deposited in a hollow, for its base is concave upwards and is not parallel to the general bedding.

The strip of rock exposed along the coast is so narrow, and the hinterland so poorly exposed, that it is impossible to estimate how frequently beds die out along the strike. Nevertheless it is clear that lenticularity can be demonstrated on occasion.

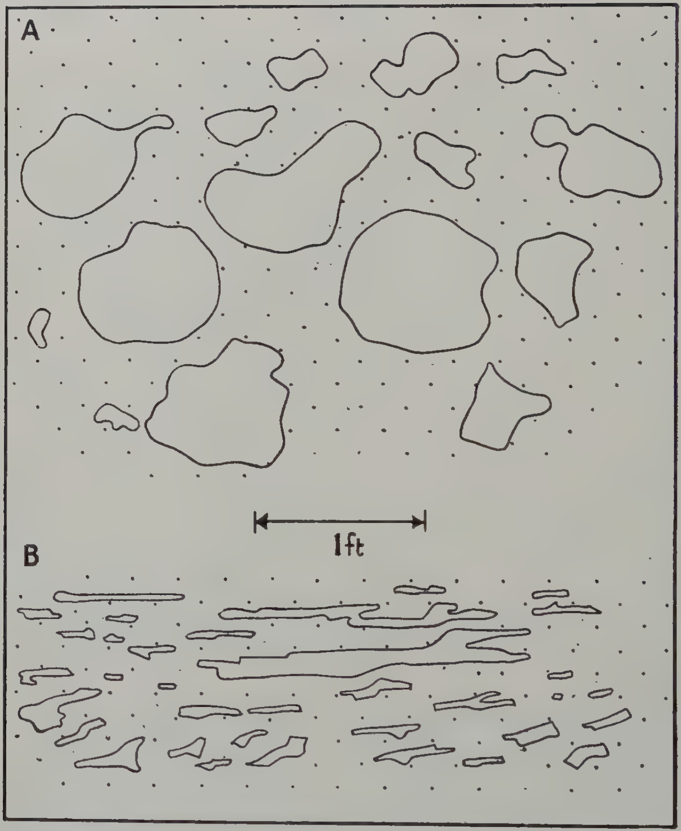


Fig. 1. Mudstone fragments (no ornament) in graded grit (dotted): (a) Fragments as seen looking down on a bedding-plane, showing disc-like form; (b) Fragments in section perpendicular to bedding, showing angular outline

*Fragments of slate or mudstone.* Perhaps the most striking feature of the Banffshire grits is the presence of abundant mudstone-fragments in many of the grit bands (Figs 1, 2; Plate 4, A). R. Walls (1937) was the first to suggest that these fragments resulted from submarine disturbances, and attributed to slumping examples which he noted near Banff. Although some occurrences of mudstone-fragments, such as are described later, seem to have been formed in this way, the majority appear to us to have been laid down in their present form when the enclosing bed of grit was deposited.

The shale-fragments (Fig. 1 a) are plate-like in form, the flat surfaces being bounded by bedding planes and the corners being sharply angular (Fig. 1 b). Commonly they are 4 in. to 9 in. long and ½ in. to 2 in. thick, but sometimes they reach 2 ft. in length. Frequently they are curved or intensely contorted, showing that the rock of which they are made was still soft when it was caught up (Fig. 2). As a rule the fragments lie parallel to the bedding, though they may be tilted, and occasionally lie at right-angles to the bedding.

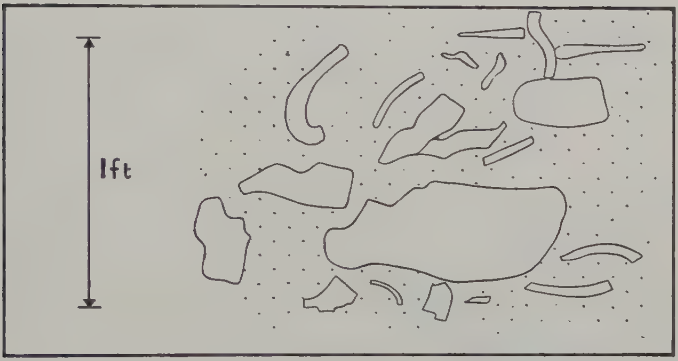


Fig. 2. Bent mudstone fragments (no ornament) in graded grit (dotted); section perpendicular to bedding

The abundance of mudstone-fragments in the graded grits varies erratically from one bed to another. One bed may contain none at all, although in a neighbouring bed, identical with the first in all other respects, the fragments may be so abundant as to touch each other. Within a single bed, on the other hand, the proportion of shale-fragments remains practically the same throughout the longest available exposures (which provide strike-sections up to 400 ft. in length).

Unless the fragments are so numerous as to fill the entire thickness of a bed they are generally concentrated at some particular level in it. We expected that they would prove to be consistently concentrated at the tops or bottoms of beds, but we encountered examples where the fragments were concentrated at the bottom, and others where they had accumulated at higher levels in the grit bands. A similar irregularity in the distribution of clay-fragments has been reported from other examples of deposits of this type. In Tertiary beds of the Apennines, Kuenen & Migliorini (1950, p. 111) found that, as a rule, the flakes are not concentrated near the base of the beds but commonly lie in the middle or upper sections; Natland & Kuenen (1951, p. 90) have described shale-fragments isolated, or in groups, in the lower parts, or at high levels, in the sandy beds of the Tertiary Ventura Basin in California. Kuenen and Migliorini have emphasised the fact that the presence of clay-fragments high up in a graded bed must mean that such fragments did not roll along the sea-bed to reach their present position.

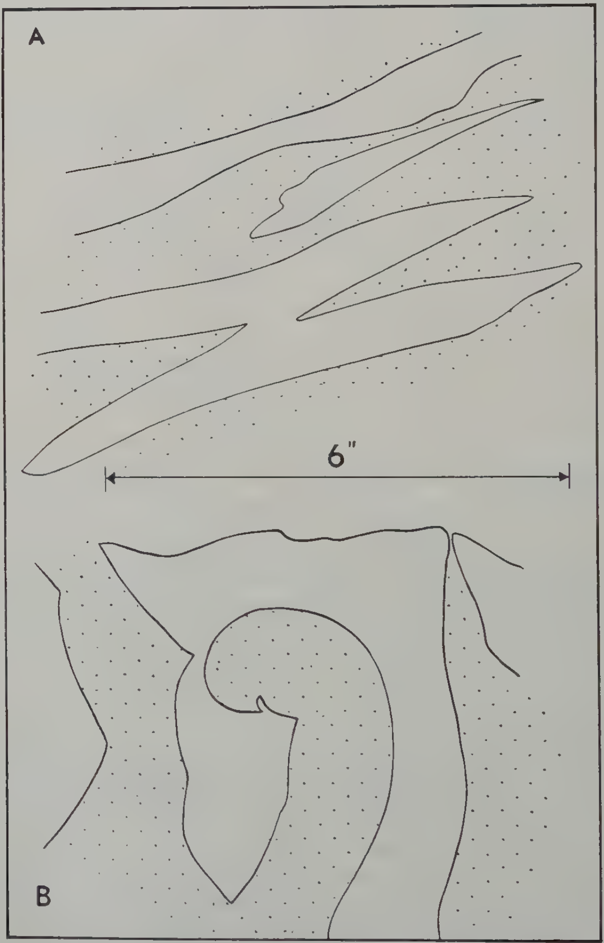


Fig. 3 a. Grit veins (dotted) injecting muddy sediments below a grit bed; 3 b. Grit (dotted) invading mudstone

The evidence as to the source of the clay-fragments in the Banffshire deposits, and the distance they have travelled, is not wholly consistent.

At some localities grit appears to have been injected into the muddy sediments beneath, in the form of a network of veins approximately parallel to the bedding (Fig. 3 a), or in curved and flowing shapes (Fig. 3 b); fragments might be detached from such a *mélange* and included in the grit lying immediately above, and in such instances very little transport of fragments would take place. On the other hand, many grit-bands contain a mixture of several lithological varieties of mudstone-fragments, any or all of which may differ from the rocks underlying the grit. Again, grits with mudstone-fragments may rest directly on other grits, or siliceous rocks. In such instances the fragments must have been carried at least some distance, and were not derived from the immediately underlying rock. It might be argued that the grit had stripped off an underlying mud-band of which no trace remains, but against this are the many examples where the muddy top of an underlying graded bed has been preserved below a later grit, without erosion.

As already mentioned, the mudstone fragments, although obviously fairly soft when they were transported, are very angular. Both features are frequently reported in accounts of beds of this description (Henderson, 1935, p. 500; Kuenen & Migliorini 1950, p. 111). When fragments such as these lie at the base of a grit-band they might represent a locally-formed breccia, but the fragments high up in a graded grit, must have been transported, as has been pointed out. Their angularity indicates that they have not been rolled along the sea-floor. This evidence suggests that the angular mudstone-fragments in the Banffshire grits were carried in a medium of high density and that the fragments settled into their present positions as the graded bed was deposited from a submarine mud-river or turbidity-current.

*The tops and bottoms of graded beds.* Many of the graded beds have flat tops and bottoms, and it is difficult to say whether or not erosion took place before the deposition of the next bed. In some localities, however, a fine-grained deposit lying beneath a grit-bed is deformed in a manner which shows that it must have been in the condition of a soft mud when the grit was laid down on top of it. The preservation of this mud indicates that little or no erosion preceded the deposition of the grit. On the other hand, grits in other localities fill washouts, or truncate structures of the bed beneath, and here it is plain that erosion has occurred.

Irregularities of another type are seen in some beds, the bases of which show rhythmic undulations, often with short cusps directed upwards. The wavelength of such a structure near Banff Gasworks varies from 4 in. to 1 ft. 6 in., and that of one in Gamrie Bay reaches 3 ft. The lowest layer of the succeeding bed follows the undulations, and the hollows are filled with

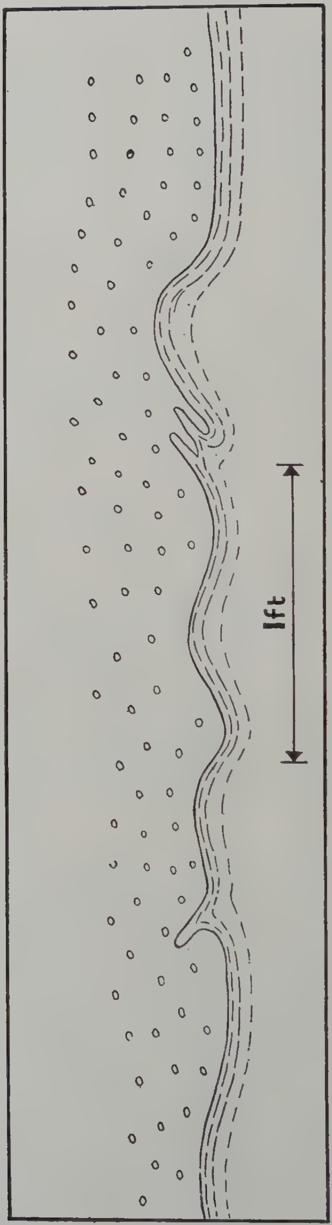


Fig. 4. Silty mudstone bulging beneath an overlying graded grit bed

material coarser than the rest of the bed, showing that the undulations formed early enough to affect the deposition of the following bed. A more complex structure can sometimes be seen at the junction of grits and shales, e.g. near Blackpots Harbour (Fig. 4) where the shale appears to have moved under the overburden to form domes and hollows. The veining of a shale by grit, at the base of a grit-band, has already been described, and is illustrated in Fig. 3.

*Washouts*. Examples of lenticular pebbly beds, resting in eroded hollows in the beds below, have been mentioned already. Only about six such beds have been found, and all are abnormally coarse, with pebbles more than half an inch in diameter. None of them is graded.

*False bedding*. In rare instances false bedding occurs in grit bands. It may be seen on the shore below Banff Station, and again at Elf Kirk, half a mile farther west. False bedding is much more frequently developed in the finer-grained gritty deposits described below.

(ii) *Small-scale graded bedding* (*greywackes and flags in beds a few inches thick*)

*General characters*. The rocks described in this section form beds which are seldom more than 3 in. in thickness, and commonly less than 2 in. in thickness. They consist of finer-grained material than the grits, the largest grains being less than a millimetre in diameter as a rule. They are among the commonest rock-types of the Banff Division and can be found in the Whitehills Group eastward from the west of Stake Ness, and throughout the subsequent members of the succession.

The main characteristic of these rocks is the excellence of the grading, as a result of which each bed began with a predominantly sandy portion and ended with a predominantly muddy part. On the sea-scoured rock-faces of the coastal section the gradation is marked by a change of colour from yellow-green to dark green. Some of the graded beds to the west of Banff, in which Read (1936, p. 473) noted the formation of andalusite in the clay-rich portion, fall into this group.

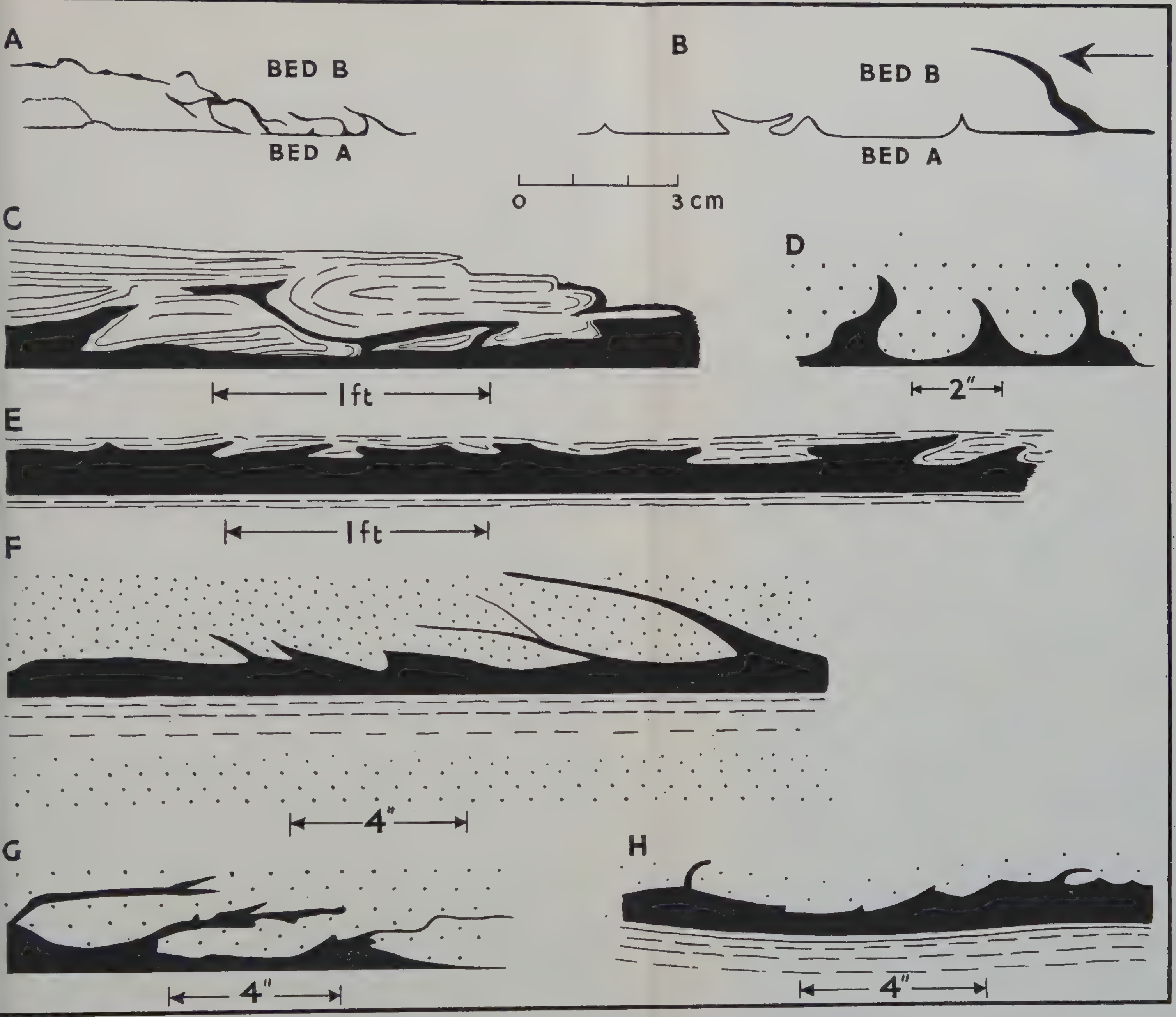
In thin-slice, the coarsest parts of these graded beds resemble the finer parts of the graded grits. Angular or partially-rounded grains of quartz and oligoclase lie scattered through a matrix consisting of still smaller chips of the same minerals, and of micaceous material reconstituted from the clay-fraction of the original sediment. The changes induced by progressive metamorphism have been described, in detail, by Read (1923, pp. 54, 55, 58, 59 and 63). In each graded bed the fine-grained upper part resembles the matrix of the lower part, deprived of all its larger clastic grains.

Variations in the proportion of the relatively coarse material affect not only the appearance but also the thickness of each bed. Any series of beds is either uniform, or shows a progressive change in thickness. At one extreme, the sandy part is reduced to a mere film and the rock approaches very near to a shale in composition. At the other extreme, the beds have a truly gritty base, and may be a foot in thickness. This latter type generally remains distinct from the grits which were described above, where particles visible to the naked eye are found throughout the thickness of a bed, and there is no real transition between the groups.

*Tops and bottoms of graded beds.* The gritty base of a graded bed often lies on the muddy top of the bed below, without any disturbance of the latter. In many instances, however, the contact of two such beds is contorted. The contortion may be restricted to a gentle sagging and doming, such as has been illustrated in Fig. 4; flame-like tongues of mud may intrude the overlying bed (Fig. 5 d), or thin lamellae of the underlying bed may be insinuated between wedge-shaped masses of the overlying coarse bed (Fig. 5 f). Particularly complex structures are sometimes formed when the overlying bed is itself fine-grained; in such cases the muddy top of one bed and the silty base of the next form a series of interlocking pockets, such as are shown in Fig. 5 e. Such structures may become yet more complicated and the pockets of silt may give rise to lenses of silt which are nearly, or completely, enclosed in what had originally been the underlying mud (Fig. 5 c). Structures of this nature are hardly to be distinguished from slump balls, yet are sometimes restricted to a layer an inch or two in thickness at the base of a bed, the top surface of which is a normal undisturbed bedding plane. In such cases it seems clear that the overlying bed cannot have moved across the sea-floor as a slump-sheet after its deposition, and that the deformation accompanied the deposition of the bed.

The most satisfactory explanation of these contortions is that they result from the doming and sagging of watery muds under the influence of the newly-added load of a succeeding bed. When the latter is deposited by a current, horizontal movements may combine with the vertical displacements to give the flame- or wave-like forms, and the slumped lenses illustrated in Fig. 5.

Figs. 5 a and 5 b show structures produced by Kuenen during experiments in which suspensions of mud and sand were poured down a channel under water and settled to form graded beds (Kuenen & Menard, 1952). The similarity between these artificially-produced structures, and those at Banff, suggests that the latter were also formed by turbidity currents. Similar structures have been described from other localities, where an alternation of muds and coarser sediments has been deposited. An example from Langdale was attributed by Sorby (1908, p. 197 and pl. XIV) to the breaking-up of a semi-liquid fine-grained deposit by currents which brought a later deposit of ash. Henderson (1935, pl. II, fig. 3) illustrates 'wave crests formed in semi-liquid mud by currents which brought forward the overlying sand' (p. 509) from Ordovician sediments at Girvan showing many other similarities to rocks of the Banff Division. Shrock's 'flow-casts'



ig. 5. Structures formed at the junction of successive graded beds: (a) and (b) Structures produced artificially by Kuenen at the contact of experimentally-formed graded beds; ) Pockets and balls of silt collapsing into underlying mud. Banff; (d) 'Candle-flames' of mud intruding the base of the succeeding grit. Old Haven; (e) Pockets of silt sinking to the underlying bed, Banff; (f), (g) and (h) Base of graded grits, veined by mud from the underlying beds, Old Haven

[*To face p.* 116

(1948, p. 156) are identical with some of the Banffshire examples. Natland & Kuenen (1951, pp. 96–9) present a discussion of flow-casts, pockets and slump-structure of this nature. They illustrate a case where silty clays have bulged under an over-burden of graded sandstone which resembles the example illustrated in Fig. 4 of this paper (Natland & Kuenen, 1951, p. 99, fig. 19). These authors are of the opinion that 'pockets and flow casts are formed by subsidence under unequal loading, but with crinkled bedding a certain amount of horizontal sliding may have been added. Pseudo-nodules (slump balls) result from combined vertical and horizontal movements, and in slump structures the sliding predominates or acts alone' (Natland & Kuenen, 1951, p. 98).

The crinkled bedding referred to above is a contortion formed in the upper parts of graded beds. Migliorini, who observed it in the Macigno of northern Italy (1950, p. 88—'stratificazione arricciata'), believed it to be the result of the trapping of water expelled from the lower parts of a graded bed while the upper parts were being deposited by a turbidity-current. We have noted structures in Banffshire resembling these, though we have not noticed any of the vertical cylindrical structures in the lower parts of the bed, below the bulges of the crinkled zone which Migliorini (1950, p. 89) found in Italy, and attributed to the upward movement of the water.

*Current bedding*. The small-scale graded beds provide many examples of the combination of graded bedding and current bedding. The more sandy portion at the bottom of a graded bed is frequently false-bedded on a very small scale, the height of the false beds being often less than one inch. These beds recall a similar association in the Ordovician rocks at Girvan which has been mentioned by Henderson (1935, p. 497).

A second type of false-bedded rock, though not itself graded, may occur as intercalations in series of flaggy graded beds. This rock forms isolated beds, two to five inches in thickness, which are usually flanked by an inch or so of massive siliceous rock (Plate 4, B). The whole assemblage can be traced continuously along the strike for as much as 150 ft. The false-bedded portion is often ripple-marked at the top and bottom, and the inclined bedding appears to record the lateral migration of the ripples. The false-bedded bands are generally somewhat calcareous and in the region of higher-grade metamorphism, west of Banff, show a beautiful development of prismatic amphibole and of garnet.

*Graded beds with boulders*. Immediately to the east of Macduff, and again to the east of Head of Garness (Plate 3), there occur ten or twenty feet of well-bedded graded greywackes which differ from the rocks described above in containing sporadic exotic boulders and pebbles, ranging in diameter from three feet downwards, and consisting of igneous and metamorphic rocks. This deposit has been described in detail elsewhere (Sutton & Watson, 1954). The boulders, which include among rock-types granite, a syenitic rock, siliceous granulite, quartzite, limestone and vein-quartz, do not appear to have been transported along with the greywacke matrix, but seen to have been dropped into it from above. Although we have considered very carefully the possibility that the boulders have been brought down by turbidity-currents or by slides from nearby cliffs, it seems more likely that they were carried by floating ice. It is not quite certain whether the two exposures, which are about two miles apart, are parts of the same horizon, but both lie between 1500 and 2000 ft. above the top of the Whitehills Group.

(c) **Slump sheets.** Walls, who was the first to recognise slumping in the rocks of the Banff Division, described its effects in two localities—at Scotstown, Banff, and near Rosehearty in Aberdeenshire, fifteen miles to the east (Walls, 1937, pp. 22–7). At Scotstown, he recorded the bulging of grit into mudstone, the wedging-apart of siltstone by grit, the formation of siltstone-fragments and the squeezing of quartz pebbles into the outer layers of such fragments. Although no clear distinction was made between the inclusion of mudstone-fragments in graded grit beds—a phenomenon which we believe to be due largely to the action of turbidity-currents—and other structures which appear to us to be due to slumping, nevertheless Walls entertained the idea of a two-fold process: 'the structures have been formed by the sliding of the partly consolidated sediment on the sea floor. . . . The movement was sufficiently violent to break up some of the partly consolidated siltstone, fragments of which became included in the sandy beds, which, when in motion would have a semi-fluid character. . . . It is tempting, but the evidence is not decisive, to ascribe the graded beds above the "mixed rock" of Black Rock to the gradual settling out of material from water disturbed by sliding' (pp. 26–7).

Slumped sheets have been encountered by us at many other localities (Figs.6–9) and they seem to have been formed at intervals throughout the deposition of the rocks higher than the calcareous part of the Whitehills Group. Coarse grits are seldom slumped, but slumping of finer-grained but still thick-bedded siliceous rocks, and of thin-bedded greywackes, flags and slates, has been observed. All these types show a characteristic knobby weathering which distinguishes them from the evenly-bedded rocks.

The two thickest, and as far as can be ascertained the most extensive, slumped sheets are formed of predominantly argillaceous rocks. One appears on both sides of a complex syncline at Scotstown, Banff; the other, which reaches 50 ft. in thickness, is repeated by folding along the shore south of Banff Harbour, and very possibly extends as far east as Macduff Harbour. The mode of exposure makes it impossible to determine whether each sheet is continuous, or whether there are several smaller sheets, keeping to approximately the same two horizons.

Beds of slumped siliceous rock do not as a rule reach a thickness of more

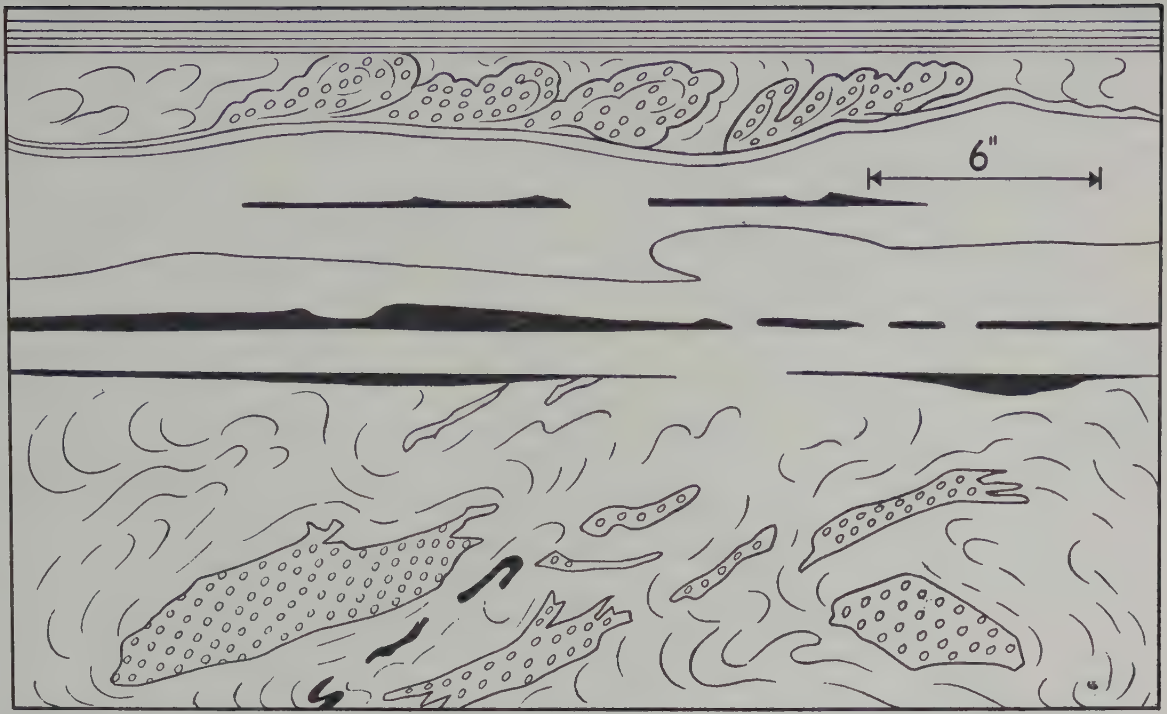


Fig. 6. Slip-folding and slumping, Boyndie Bay. Calcareous bands (black) show ‘pull-apart’ structure; andalusite-bearing pelites (dotted) form slump-balls in folded semi-pelite

than 10 ft., but several such sheets may follow each other, with no intervening bedded sediment or, more commonly, with a few feet of well-bedded flags or grits between the successive sheets. At Old Haven, for example, slumped beds can be seen at intervals between tide-marks throughout the western half of the bay. To the west of Gardenstown eight slumped sheets, separated by well-bedded sediments, occur in one 50-ft. sequence. The lack of inland exposures makes it impossible to determine the lateral extent of the sheets.

Varying degrees of disturbance can be seen at different localities within the argillaceous slumped sheets at Banff. Some exposures show structures suggesting that they became unstable without actually moving far, while others appear to have undergone considerable movement. The first signs of disturbance can be seen, for example, in the more easterly exposure of the sheet below Scotstown, or in the south-west part of Boyndie Bay, 400 yds. south-east of Red Well (Fig. 6). Here, the harder calcareous bands (now metamorphosed into a calc-silicate rock) have been broken up into fragments which remained roughly aligned while the surrounding mudstones (now forming spotted andalusite-rocks) began to flow and fold.

This structure, which Natland & Kuenen (1951) call ‘pull-apart’, is rather similar to tectonic boudinage, but on the Banffshire coast there is little danger of confusing the two, since the structures of ‘pull-apart’ type are associated with other signs of slumping, and since the rocks in which they are found are in contact with normally-bedded rocks showing no signs of tectonic disturbance. In boudinage, the soft rocks generally flow towards the gap in the hard bands; in slumped rocks the structure of the mudstone bears no relation to the position of the harder inclusions, the muddy material having apparently slid, in an almost fluid condition, around the inclusions.

Further movement in a slumped bed disarranges the broken-up fragments and converts the rock into a *mélange* of contorted argillaceous material with siliceous and calcareous lumps in it (Fig. 7). The matrix forms irregular, flowing folds (Fig. 8) while the intercalated harder bands were squeezed, kneaded and folded in an irregular manner. Hard blocks sometimes act as the cores of folds in the argillaceous rocks, and in this way slump-ball structures like those described by Kuenen (1949, figs. 3 and 4) from the Pembrokeshire Coal Measures, are developed.

In the westernmost exposure of the Scotstown slumped sheet, west of Elf Kirk, and again in the beds between Banff Harbour and the River Deveron, irregular masses of calcareous and siliceous rock occur in a completely haphazard manner in an argillaceous matrix. Some parts of the matrix show flowing folds, and local traces of the original small-scale graded beds can still be found, but other parts are entirely structureless as a result of the destruction of the original bedding (see Fig. 7). The disap-

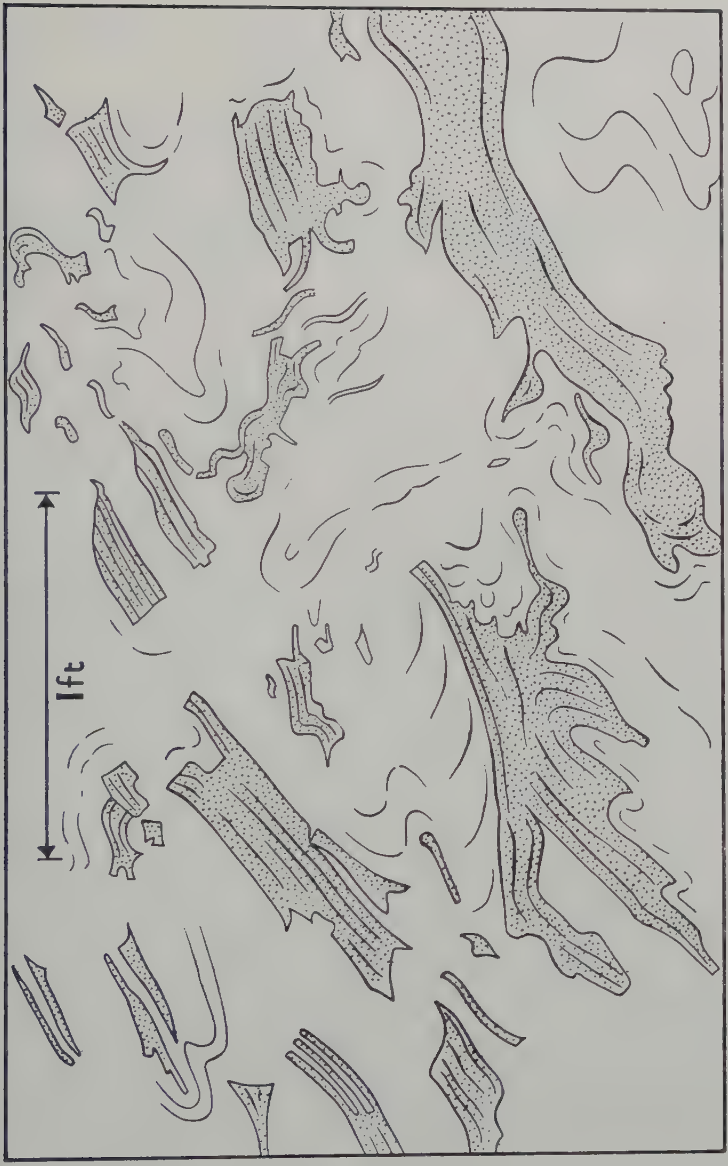
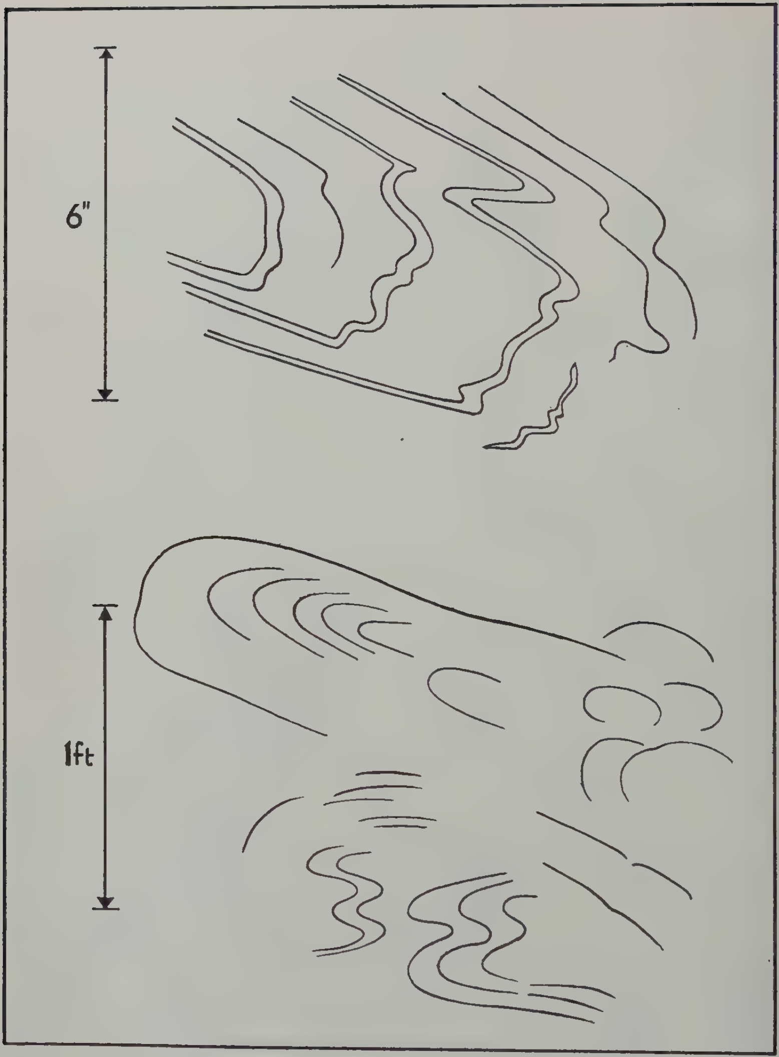


Fig. 7. Slump-balls and slump-folds, Elf Kirk, Scotstown. Disrupted siliceous and calcareous fragments in an argillaceous matrix which is losing its bedded structure



Figs. 8 a and 8 b. Slump-folds in argillaceous slump-sheets

pearance of the bedding suggests that the slumped mass lost its coherence locally, and reached the state of a turbid flow.

In rocks made up of rapid alternations of sandy and muddy material, slumping produces a very striking effect. A rock immediately west of the natural arch in the Howe of Tarlair shows abundant small folded or rolled-

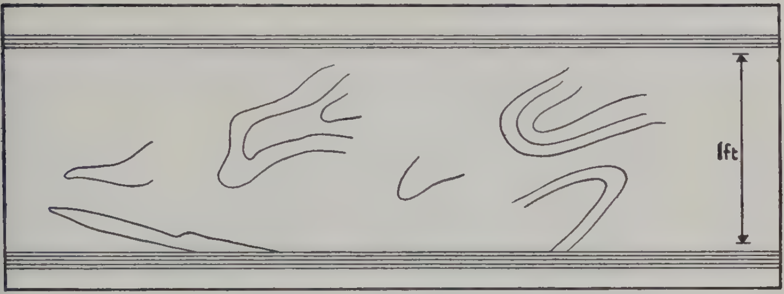


Fig. 8 b

up fragments of light-coloured sandy rock, set in a more argillaceous matrix. This exposure recalls the crumpled sandstone-balls figured by Kuenen (1949, pl. XXII, fig. 5) from Pembrokeshire.

Slumping of the thicker-bedded siliceous rocks produces less complicated internal structures. Traces of irregular swirling folds, and patches of alien rock-types, are often discernible, however. The outlines of the alien patches are blurred, as if the two rocks had been shaken violently together, and a mixed zone, perhaps half an inch wide, may surround the inclusions.

The patches of alien rock in slumped siliceous sheets sometimes have a diameter equal to the thickness of the slumped sheet. These inclusions have not been plucked up from the underlying beds, for the latter are virtually undisturbed. They are probably fragments of subordinate rock-types intercalated in the siliceous series when it began to slump. If this is so, the siliceous rocks forming the bulk of the slump-sheet must be the attenuated remainder of what was originally a much thicker series. If exotic blocks, say 1 ft. 6 in. across the bedding, make up 10% of a slump-sheet which is now itself about 1 ft. 6 in. thick, this sheet must have been derived from about 15 ft. of sediments.

The tops and bottoms of siliceous slumped beds are generally irregular and contorted, and on weathering, give rise to a surface almost like a pillow lava. The irregularities are not usually systematic but occasionally a rough series of troughs and ridges is developed. In the cleft at the tip of Head of Garness such ridges are well displayed on an inaccessible vertical bedding-surface where they plunge 040 at 15°, but structures of this kind are too rare to serve as indices of the direction of travel of the slump-sheets.

*Margins of slumped sheets.* At Old Haven, and in the Howe of Tarlair, what appear to be the noses of slumped sheets are exposed. In each locality (Fig. 9) there is a rapid change of facies along the strike, slumped siliceous rocks passing into a *mélange* with fragments of contorted rock embedded in contorted shale, and then, after a few feet, into well-bedded shale.

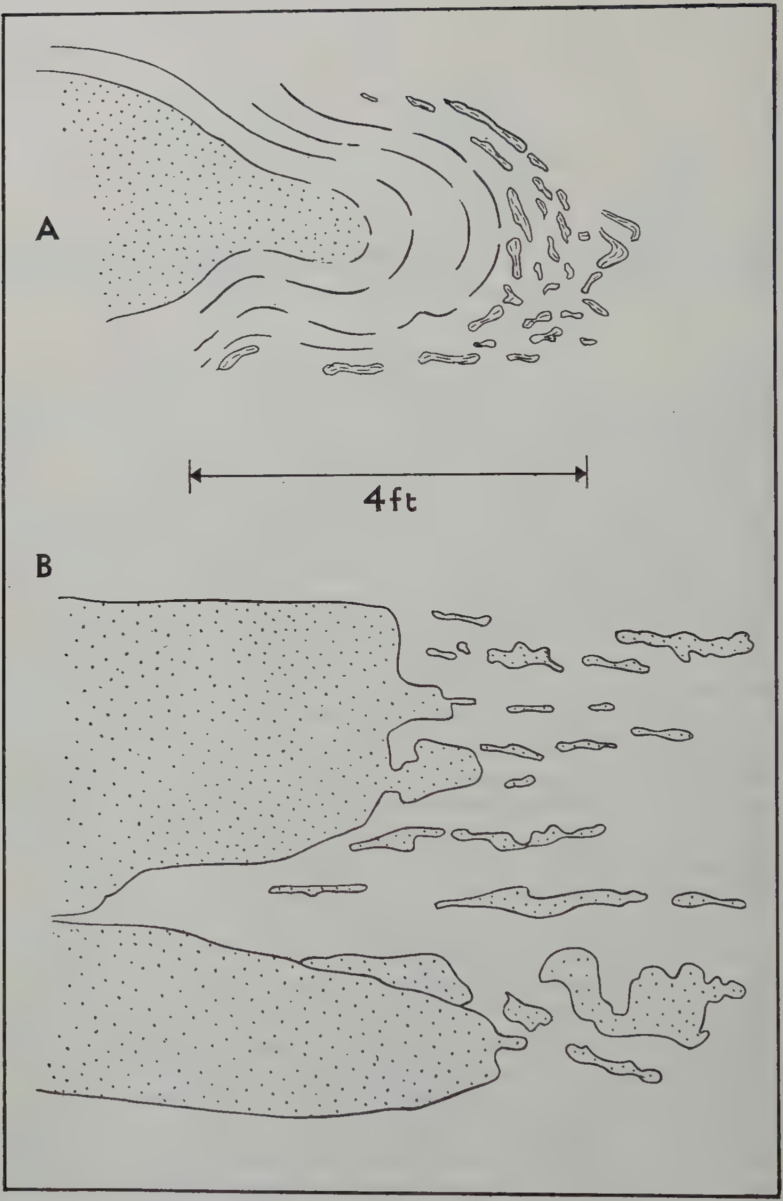


Fig. 9. Disturbance at margins of siliceous slumped beds. Siliceous rock dotted, argillaceous rock unornamented: (a) Howe of Tarlair; (b) Old Haven

## 4. CONDITIONS OF DEPOSITION OF THE UPPER DALRADIAN

(a) **The sequence of deposits.** The greywackes and grits of the Banff Division are quite unlike any of the rocks of the underlying Keith Division. Nevertheless there is no sudden change in sedimentary facies at the junction of the two divisions, and the Boyne Limestone, the lowest member of the Banff Division, would not be out of place among the limestones, quartzites and argillaceous rocks that make up the lower part of the Dalradian sequence. Indeed the Boyne Limestone might be regarded as the last deposit of this type in the north-east Scotland succession.

If we suppose the Boyne Limestone to represent a time when the sea-floor was covered by calcareous muds, the succeeding Whitehills Group marks a period when these muds were increasingly contaminated by coarse detritus derived from a land-mass. In this way a series of calcareous grits was formed, which make up the lower part of the Whitehills Group. The higher members of this group, and the whole of the two succeeding groups, consist of shales, grits and greywackes with very little calcareous matter. All three assemblages, the limestone, the calcareous grits and the greywacke-grit-shale assemblage, are linked by passage beds, and there is no doubt that this is a true upward stratigraphical succession.

A sequence such as this, over 13,000 ft. thick, implies crustal instability. Not only must the floor of the basin have sunk, but a neighbouring land-mass must have emerged to provide the clastic sediments. The coarseness of some of the deposits; the abundance of felspars; the bad sorting and the angularity of the component grains suggest that the relief remained high and that deep water lay near to an uplifted land-mass. Such conditions of emerging land near a foundering trough mark a change from those under which the relatively well-sorted deposits of the Lower Dalradian might be expected to have formed. Before considering the possible wider implications of this change it will be convenient to examine the evidence provided by the smaller structures of the Upper Dalradian sediments of the Banffshire coast.

(b) **The formation of the deposits.** *Environment.* The possibility that the Upper Dalradian is terrestial can be eliminated. The presence of thick calcareous beds; the prevalence of grading and the evidence that the argillaceous beds were highly plastic, and hence probably saturated with water, all show that the rocks were aqueous deposits. We have found no conclusive proof that they are marine, but their great extent (400 square miles of these rocks are preserved in the Turriff Syncline); the amount of calcareous material and the exceedingly close similarity between the rocks of the Banff Division and certain fossiliferous successions, are points strongly suggestive of a marine origin.

*Conditions on the Upper Dalradian sea-floor.* Although many of the rocks of the Banff Division are very coarse, the evidence discussed below suggests they are not shallow-water deposits but were formed under some conditions that allowed coarse material to be carried out into deep water. Kuenen and Carozzi (1953, pp. 364–5) have recently summarised the characteristic features of coarse deposits of deep-water origin. Of the sixteen features which they mention, the following are exhibited by rocks of the Banff Division:

(i) Course and fine beds are interstratified
(ii) The bedding is regular and beds rarely pinch out
(iii) Wave ripple-marks, coarse or mutually-opposed cross-bedding and channel-scour have rarely been observed
(iv) The beds are generally graded
(v) Sorting within each part of the graded beds is poor
(vi) The grit beds have sharp lower contacts and usually, also, sharp upper contacts
(vii) Load-casts are formed at the bases of grit beds
(viii) Convolute bedding has occasionally been noted
(ix) Shale inclusions are common in the grits
(x) The thickness of the bed is generally proportional to its grain-size
(xi) Each bed tends to maintain its special characteristics, such as load-casts, over its entire length, in any exposure.

In some examples of this type of sedimentation, decisive evidence is provided by the juxtaposition of re-worked shallow-water faunas in the coarse beds and deep-water forms in the inter-stratified shales. Such evidence is necessarily lacking in Banffshire, but it seems legitimate to apply the work of Kuenen and his colleagues to a non-fossiliferous terrain where the points of lithological similarity are so numerous. It is right to recall that the recent work on this problem has its roots in ideas put forward by Bailey, after many years of work on the Dalradian, in his classic paper on sedimentation and tectonics. Bailey (1930, p. 89) suggested that 'graded sandstone beds are often the records of sea-quakes. . . . The coastal fringe of unconsolidated current-carried sand and mud would provide a source for the material.' Later, Bailey (1938) pointed out that submarine landslips might merge into submarine mud-rivers. Both Bailey and Kuenen acknowledge their debt to Daly, who first suggested the existence of such submarine mud-rivers or turbidity-currents.

The characters of turbidity-currents have been explored in a series of papers by Kuenen and his co-workers (see especially Kuenen, 1951, 1952; Kuenen & Migliorini, 1950; Natland & Kuenen, 1951). It is held that in such currents the turbidity of the flow keeps sediment in suspension, while its high density (the result of the great admixture of sediment) enables it to carry large particles and to travel far beyond the reach of normal bottom currents.

Both Kuenen and Migliorini have shown how the characteristics of a graded greywacke assemblage may be explained by the action of turbidity-currents. If the Upper Dalradian rocks of Banffshire include members laid down by such currents, one would expect to find evidence showing (i) that they were deposited in a series of pulses of sedimentation; (ii) that the material was carried in suspension, and (iii) that they are re-deposited sediments in the sense of Migliorini (1949, p. 39; 1950, p. 82), derived from material which had been previously deposited nearer the shore. Each of these propositions is examined below.

(i) *The beds were deposited during pulses of sedimentation.* As the majority of the grit beds are graded, it appears that all the material contained in one bed must have been in suspension at the same time and settled out under the influence of gravity. Yet the graded beds are many feet in thickness, a point which disturbed Read (1936, p. 472) and which indicates that large volumes of detritus must have been brought down and deposited in a single act of sedimentation. That the material settled very rapidly is suggested by the fact that mudstone fragments in the grits are sometimes tipped up at an angle to the bedding, as if they had been buried before they could subside.

(ii) *The material was transported in suspension.* The graded beds are badly-sorted, although in some instances they were transported by currents powerful enough to carry quartz-fragments one or two inches in diameter and mudstone-masses up to 1 ft. 6 in. in length. Furthermore, there is often evidence that currents of this nature passed over a muddy sea-floor without completely removing the thin muddy surface layer. It is suggested that these facts could be explained by the assumption that the graded beds were deposited from turbulent flows of relatively high density. The wave-like deformation of the muddy surface below certain graded beds closely resembles structures produced experimentally by Kuenen as a result of the passage of turbidity currents carrying material in suspension (see Figs 5 a, 6, after Kuenen & Menard, 1952).

The occurrence of mudstone-fragments high up in a graded deposit might also be explained by supposing that the whole bed was a deposit from a suspension. Thus there are three lines of evidence, explored by earlier workers on this problem in other areas, which suggest that the Banffshire deposits were transported in suspension.

(iii) *The graded beds are re-deposited sediments.* The volume of material needed to form a graded bed, say 10 ft. in thickness and with a considerable lateral extension, seems more than a normal transporting-agent, such as a river in flood, might be expected to deliver at any one time. If the graded beds were derived from the reservoir of unconsolidated coastal sediment, as Bailey suggested, their thickness would be explained more easily.

The occurrence of mudstone-fragments at high levels in graded beds, and the intermixing of several types of fragments, indicate that these fragments must have been transported, and once formed part of an older bedded sequence. As it is known that muds consolidate more rapidly than sands, after deposition, it is reasonable to suggest that a grit bed with mudstone-fragments derived its matrix from the more readily disintegrated coarse parts of such an older sequence and its fragments from those relics of the finer beds which remained as coherent masses during the submarine disturbance.

The larger clastic fragments in the graded grits are generally well rounded. These pebbles cannot have been rounded under the conditions which left soft mudstone-fragments with angular edges, and therefore they must have been formed in some other environment and transported to their present position subsequently.

The features mentioned above seem to us consistent with the hypothesis that the graded beds of the Banff Division were deposited from turbidity-currents. The occurrence of slumped beds supports the suggestion inasmuch as it shows that the sea-bottom was unstable. Moreover, locally some slump-sheets pass into rocks in which the original bedding-structures have almost disappeared. Apparently these rocks lost their coherence, and were in process of becoming a slurry, when the disturbance ceased; further movement might lead to the development of a submarine mud-river capable of depositing a graded bed.

In the graded rocks of Banffshire, the relationship between the thickness of a bed and its grain-size is so close that, given the thickness of a graded bed, one could predict its appearance. This relationship may indicate that both the large-scale and the small-scale graded beds form part of a single series in which each bed thinned from a grit to a fine greywacke as it went further from its source. If this were so, the scarcity of graded beds of intermediate size, say from 3 in. to 12 in. in thickness, would suggest that the carrying-power of the turbidity-currents decreased rather rapidly after the coarsest parts of the load had been laid down.

(c) **Source of the Upper Dalradian sediments.** No progressive lateral change of facies has been detected in the Banff Division, a fact which may be due, in part, to the difficulty of following beds inland. Two other lines of evidence remain which bear on the source of the sediment; one is the nature of the clastic particles themselves, a matter which Wilson and Read have both dealt with; the other is provided by sedimentary structures which may indicate the direction of transport of material.

White quartz, plagioclase, potash felspar, opalescent blue quartz and quartzite are, in order of decreasing abundance, the common constituents of the grits. Wilson (1882, pp. 8–9) regarded this material as 'the waste of a granite'. Fragments of pure quartz or felspar, up to half an inch in diameter, are common, and the largest pebbles reach a diameter of 2½ inches. The sizes of these particles indicate that they must be derived from very coarse igneous intrusions, or from injection-gneisses. The predominance of plagioclase over potash felspar, which characterises not only the grits of the Banff Division, but also those of the Highland Border (Anderson, 1947, p. 484) and the Loch Awe district (Hill, 1905, p. 43) suggests that potassic granites were not the chief source-rocks. Fragments of quartzite are widely distributed in the Banffshire grits, and a much greater variety of crystalline boulders (including granite, quartzite, limestone and siliceous granulite) has been found in graded greywackes at two localities. A very marked contrast between the state of crystallisation of these pebbles and boulders, and that of the greywackes enclosing them, indicates that the former existed as crystalline rocks at the time of the deposition of the Upper Dalradian. It is necessary to emphasise this, as the 'schist fragments' recorded by Gregory from Upper Dalradian grits have been shown to be mud pellets, or fragments derived from an underlying bed (Anderson, 1947, p. 505).

A small but fairly constant proportion of opalescent blue quartz, with microscopic characters like those of quartz from the charnockitic gneisses that lie west of the Moine Thrust, is present in the Banffshire grits and greywackes. A macroscopically-similar quartz has been found in the Highland Border region (Anderson, 1947, p. 484) and the south-west Highlands (Hill, 1905, p. 43). The charnockitic gneisses of the north-west Highlands are, so far as we know, the only British source of blue quartz showing needle-like inclusions. They form part of a belt which ran NNE.–SSW., to judge from the section preserved in western Sutherland, i.e. approximately parallel to, and north-west of, the Dalradian chain.

Thus currents bearing blue quartz are most likely to have entered the Upper Dalradian basin of deposition from the north-west. Since blue quartz is far less abundant than normal white quartz, in the grits, it seems likely that charnockitic rocks comprised only a small or distant part of the land-mass from which the sediments were derived. It may be suggested that the greater part of the material came from an area of sodic gneisses or igneous rocks and metamorphic sediments.

Observations of flow-marks, of rippled strata below graded beds, of false bedding, of the attitude of inclined mudstone fragments in grits and of slump-structures, have been made in an attempt to determine the direction of flow of currents, but, despite a careful search, only twenty-two such observations appeared to be unambiguous. Of these, nine show currents from the north-west quadrant, five from the north-east quadrant, six from the south-east quadrant, and two from the south-west quadrant. Among the readings in the north-east quadrant, four indicate currents from directions between north and NNE. If the scarcity of structures indicating currents flowing parallel to the length of the Upper Dalradian outcrop is a real one, there are two groups of observations indicating currents flowing at right-angles to the length of the basin; a larger group from the north or north-west and a smaller group from the south-east.

Thus two lines of argument, neither completely satisfactory, suggest that the Upper Dalradian sediments of Banffshire have been derived, at least in part, from the north rather than from the south. This possibility may be worth bearing in mind in the discussion which follows.

(d) **Tectonic environment of Upper Dalradian sedimentation.** The radical change in the nature of Dalradian sedimentation which followed the deposition of the Boyne Limestone in north-east Scotland does not appear to have been an isolated phenomenon. The gritty and argillaceous sediments of the Banff Division resemble in their lithology and structural position those of the Upper Pelitic and Calcareous Group, the Upper Psammitic Group of the Dalradian of the Highland Border (Anderson, 1947, p. 484), and those of the Loch Awe district in the south-west Highlands. In all three regions these rocks form the higher part of the Dalradian, and a prominent limestone lies at or near their base (the Boyne and Loch Tay Limestones). Still farther west similar types of grits, occurring in northern Donegal, Ireland, were equated with the Loch Awe succession by McCallien (1935, p. 438).

The more or less continuous development of Upper Dalradian greywackes, extending from Banffshire to Arran and perhaps to the north of Ireland, presents several points of interest. These rocks are unlike the Lower Dalradian and the Moine Series lying below and to the north-west of them. The Moine sediments are moderately well-sorted and the Lower Dalradian often exceedingly well-sorted (weathered quartzites have been used as glass sands). The Upper Dalradian, on the other hand, is predominantly ill-sorted.

Comparison with other areas where greywackes occur seems to justify the belief that the radical change in the type of sedimentation between the Lower and Upper Dalradian took place because continued, and geologically rapid, uplift had begun in a neighbouring region. This uplift was accompanied by a down-warping of the basin of deposition, as shown by the thickness of the greywacke series, and it appears, therefore, that some kind of folding of the crust along Caledonian lines had started by the time these sediments were laid down.

Lithologically, the Dalradian greywackes recall Palaeozoic assemblages to the south-east of the Highlands. Pringle (1946) was impressed by resemblances between the Harlech Grits and some Dalradian rocks; the sediments and depositional structures of the Banffshire Dalradian are very like those of some British Palaeozoic sequences (cf. e.g. Henderson, 1935). It is possible, of course, that the Dalradian greywackes themselves are all of Cambrian age, as is the fossiliferous Leny Limestone intercalated in the grits of the Highland Border. In any case, it is clear that they form the most north-westerly, and perhaps one of the earliest, of the Caledonian greywacke belts. Unlike the more south-easterly greywackes, however, they have been profoundly metamorphosed, and they share a common system of folding with the Lower Dalradian and the Moines. Thus, they provide some kind of a link between the metamorphic Highland rocks, with their characteristic tectonic style, and the slightly metamorphosed Lower Palaeozoic rocks to the south-east, which have a different tectonic style.

In attempting to understand the significance of the changes in Dalradian sedimentation, analogies with fossiliferous areas where orogenic movements can be dated more precisely, seem to provide the best means of approach.

The succession from limestones to calcareous grits and flags, and then to alternations of grits, greywackes and shales, which is seen in the Banff Division appears to bear some resemblance to that shown by Oligocene and younger rocks of the Northern Appennines in Italy. Here, marine sedimentation continued steadily from the Upper Trias into the Oligocene which brought a sudden spread of relatively coarse terrigenous material (Merla, 1952). The lower beds produced in this new depositional phase form the 'brecciole nummulitiche', consisting of limestone-breccias in graded beds, alternating with shales (Kuenen & Migliorini, 1950, pp. 111–12). The brecciole is overlain by the 'macigno' which consists of 2000 metres of alternating graded sandstone and mudstone. Certain rocks in the lower part of the Whitehills group appear to have something in common with the limestone-breccias of the brecciole. The macigno shows good grading, bad sorting, the presence of mudstone-flakes in the coarse beds and a lack of erosion below the coarse beds. Thus in many ways it resembles the grits at the top of the Whitehills Group, and the succeeding beds.

The interest of this comparison lies in the fact that the brecciole and macigno are thought to have been formed at the same time as the early movements which produced the Apennine chain. The first uplift took place near Elba, in the Middle Cretaceous and Oligocene, and during the Miocene new successive ridges rose to the north-east. The onset of coarse sedimentation shows a corresponding migration towards the north-east.

Again, the Flysch of the Alps, as described in Tercier's summary (1947), shows many features which can be matched by rocks in the Banff Division and was formed during, or just before, the paroxysmal Oligocene alpine movements. In more general terms, there seems to be agreement that greywackes characterise the latest infilling of a geosyncline.

These analogies suggest that, at the time of the deposition of the Upper Dalradian, the Caledonian movements had already begun, and it may be worth considering the possibility that the material forming these sediments might have been derived from newly uplifted ridges in the north-western part of the chain.

It is also conceivable that the tacit assumption in terms of which the metamorphism of the Moine and Dalradian rocks took place at the same time over their whole extent is not entirely true, and that there might have been a lateral migration of metamorphic activity. It has long been known that the Upper Dalradian of north-east Scotland is affected by a type of alteration in which andalusite, staurolite and cordierite were developed; its effects cannot be traced in the rocks to the north-west. It seems possible that regional metamorphism continued longest over that part of the trough in which the latest sediments were deposited. Also it is possible that the Caledonian metamorphism might have started first in the region uplifted by the early movements occurring in mid-Dalradian times which are indicated by the striking change in sedimentary facies distinguishing the Upper Dalradian rocks from the Moines and Lower Dalradian rocks. In other words, the metamorphism of the Moines and the Dalradian may have started first in the north-westerly parts of the chain and finished last in its south-easterly portions.

## EXPLANATION OF PLATES

Plate 3. Geological map of the Banffshire coast-section between Boyne Bay and a point half a mile east of Stocked Head

Plate 4. A. Mudstone fragments enclosed in coarse gritty greywacke, Banff. Metamorphism has produced dark spots of andalusite in the mudstone. Height of specimen 30 cms.

B. Current-bedded band in a sequence of thin-bedded graded greywackes, Howe of Tartair, Macduff. Height of specimen 15 cms.

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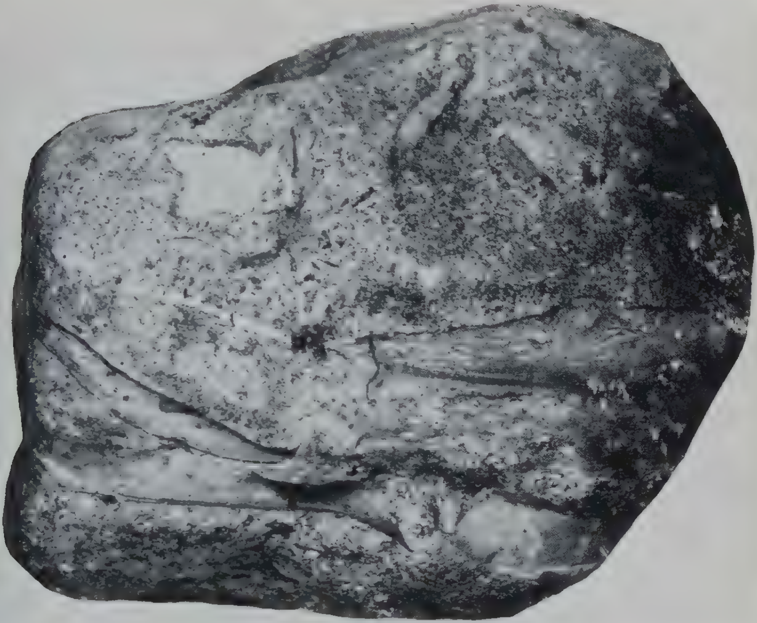

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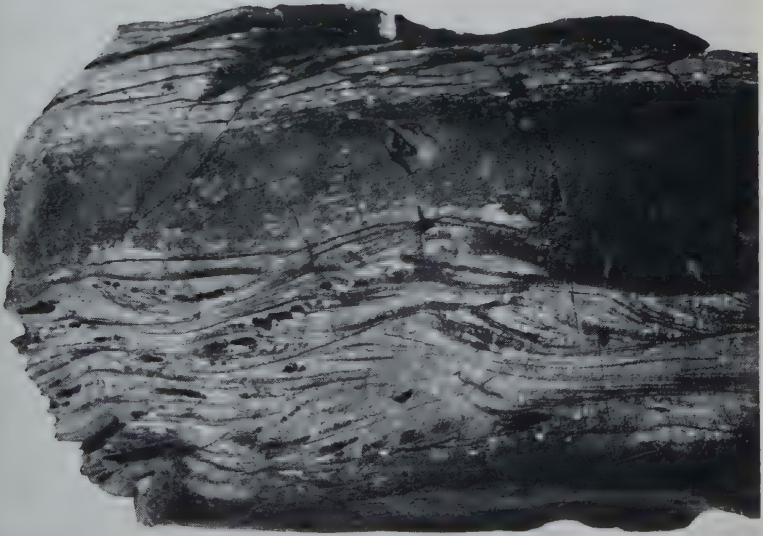

B

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## DISCUSSION

DR. W. S. PITCHER congratulated the authors on their clear and detailed description of the sedimentary features of the Upper Dalradian. The late pre-Cambrian rocks in Britain and Ireland could, and should, be treated as sediments, for metamorphism rarely obliterated all original features, certainly not along much of the length of the outcrop of the Upper Dalradian from Banff to Donegal. Indeed if fossils were once present they could well have been preserved throughout large parts of the Donegal succession.

The study of facies and sedimentation structures was probably one of the most fruitful lines of attack on the problem of correlation within the Dalradian.

# The Annual Report of the Council of the Geologists' Association for the Year 1954

THE NUMERICAL STRENGTH of the Association on 31 December 1954, was as follows:

| | |
|---|---|
| Honorary Members ... ... | 19 |
| Ordinary Members: | |
| Life Members (compounded) ... | 172 |
| Annual Subscribers ... ... | 1690 |
| | 1881 |

During the year 116 new members were elected, and the Association lost 195 members through death, resignation and removals under Rule XI for failure to pay subscriptions.

Thus, the membership has suffered a net loss of seventy-nine.

The list of deceased members is as follows: H. A. Baker, H. F. Barke, W. S. Boulton, H. Busbridge, J. T. Dodd, Sir L. L. Fermor, R. Gilling, J. C. M. Given, Miss D. E. Harvey, Prof. G. Hickling, P. E. N. Hitchins, H. Homeshaw, T. A. Jones, W. E. F. Macmillan, A. J. Maslen, H. F. Morgan, M. A. Ockenden, Miss E. Pearse, R. W. Pocock, W. P. Powell, H. Rutledge, N. Stein, S. Waller and C. Worsford.

Obituary notices are published on page 155.

## FINANCE

Our accounts for 1954 are presented in the same form as last year with the addition of the comparable figures for 1953. The Income and Expenditure Account shows a slight increase in income from Subscriptions, £1390 12*s*. 2*d*. for 1954 against £1383 for 1953, but a steep rise in arrears. Of the £808 3*s*. 6*d*. arrears with which we ended the year, £344 9*s*. 0*d*. results from members who are three years in arrear and are being removed. As the payments on arrears in 1954 were disappointing and failed to reach the estimated realisation amount the balance still outstanding has been written down to £250.

One item in the Income and Expenditure Account calls for explanation, the cost of the PROCEEDINGS includes a reserve of £200 towards the cost of

Part 4. In previous years the accounts have shown the actual expenditure during the year on four parts and have made no allowance for the liability we have to send Part 4 to all 1954 subscribers. The inclusion of this reserve puts our financial position on a more realistic basis.

Under the will of the late Prof. W. E. Skeats we were left a legacy of £500 (Australian money) and this was received during the year, realising £402 7*s*. 9*d*. sterling. On the recommendation of the Trustees the following investments were made: £400 of the Skeats legacy in British Transport Stock and £282 2*s*. 0*d*. of the cash balance in the Compounding Fund in 3½% Treasury Stock. The publication of the Ten Year Index for 1940–9 considerably reduced the Indexing Fund and this has been partially redressed by a transfer of £100 from the general funds.

The Council of The Royal Society has again assisted us with a grant of £300 (in addition to the £50 granted at the end of 1953 and received in 1954) from the Parliamentary Grant in aid of Scientific Publications.

Our position is stronger than last year, but the arrears are still unsatisfactory. It will be obvious to all that with over twenty per cent of members in arrear the work of the Association must be seriously hampered.

## BALANCE SHEET AT 31 DECEMBER 1954

Statement 1

| 1953 £ | | £ s. d. | £ s. d. | £ s. d. |
|---|---|---|---|---|
| | TRUST FUNDS AND FUNDS FOR SPECIAL PURPOSES: | | | |
| 3830 | Capital ... ... ... ... | | | 4511 12 4 |
| | Accumulated Income: | | | |
| 282 | Bequest Fund (Statement 3) ... | | 306 8 5 | |
| 6 | Centenary Fund (Statement 4) | | 40 13 1 | |
| 297 | Compounding Fund (Statement 5) ... ... ... ... | | 71 15 10 | |
| 73 | Illustrations Fund (Statement 6) | | 22 18 7 | |
| 141 | Indexing Fund (Statement 7) ... | | 121 13 10 | |
| 135 | Watts Charnwood Forest Fund (Statement 8) ... ... ... | | 150 11 0 | |
| 26 | Foulerton Award Fund (Statement 9) ... ... ... | | 26 15 9 | |
| 80 | G. W. Young Geological Investigation Fund (Statement 10)... | | 42 10 9 | |
| 22 | Henry Stopes Memorial Fund (Statement 11) ... ... | | 29 10 9 | |
| | | | | 812 18 0 |
| 1062 | | | | 5324 10 4 |
| | GENERAL FUNDS: | | | |
| | General Reserve: | | | |
| | Balance 1 January 1954 ... | 336 4 5 | | |
| 336 | *Add* Post Office Interest ... | 31 14 4 | | |
| | | | 367 18 9 | |
| | Income and Expenditure Account: | | | |
| | Balance 1 January 1954 ... | 253 15 8 | | |
| 254 | Surplus for Year (Statement 2) | 175 19 11 | | |
| | | | 429 15 7 | |
| 590 | | | | 797 14 4 |
| £5482 | | | | £6122 4 8 |

| 1953 £ | | £ s. d. | £ s. d. | £ s. d. |
|---|---|---|---|---|
| | TRUST FUNDS AND FUNDS FOR SPECIAL PURPOSES: | | | |
| 3830 | Investments (Statement 12) ... | | | 4511 12 4 |
| 10 | Income Tax Recoverable ... | | 4 3 1 | |
| 1052 | Cash at Bank and Post Office ... | | 808 14 11 | |
| | | | | 812 18 0 |
| 1062 | | | | |
| 4892 | | | | 5324 10 4 |
| | GENERAL FUNDS: | | | |
| 230 | Subscriptions in Arrears ... ... | | 250 0 0 | |
| 4 | Admission Fees in Arrears ... | | 2 10 0 | |
| 704 | Cash at Bank, Post Office and in Hand ... ... ... ... | | 959 11 8 | |
| 938 | | | 1212 1 8 | |
| | *Less* Admission Fees in Advance | 9 10 0 | | |
| 103 | *Less* Subscriptions in Advance ... | 106 10 5 | | |
| 245 | *Less* Accrued Expenses ... ... | 298 6 11 | | |
| | | | 414 7 4 | |
| 348 | | | | 797 14 4 |
| 590 | | | | |
| £5482 | | | | £6122 4 8 |

# INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31 DECEMBER 1954

Statement 2

## EXPENDITURE

| 1953<br>£ | | £ | s. | d. | £ | s. | d. |
|---|---|---|---|---|---|---|---|
| 1388 | "PROCEEDINGS" OF THE ASSOCIATION ... ... | | | | 1530 | 10 | 3 |
| | GENERAL EXPENSES: | | | | | | |
| 105 | Accountancy ... ... ... ... ... | 42 | 0 | 0 | | | |
| 32 | Addressing and Stock-keeping ... ... | – | – | – | | | |
| 12 | Field Meetings Expenses ... ... ... | – | – | – | | | |
| 2 | Insurance ... ... ... ... ... | 2 | 2 | 2 | | | |
| 56 | Meetings Expenses ... ... ... ... | 54 | 19 | 4 | | | |
| 197 | Postages ... ... ... ... ... ... | 167 | 6 | 10 | | | |
| 154 | Printing and Stationery ... ... ... | 89 | 18 | 4 | | | |
| 232 | Printing Monthly Circulars ... ... ... | 187 | 13 | 3 | | | |
| 9 | Sundries ... ... ... ... ... ... | 9 | 0 | 5 | | | |
| | | | | | 553 | 0 | 4 |
| 799 | | | | | | | |
| 2187 | | | | | 2083 | 10 | 7 |
| — | TRANSFER TO INDEXING FUND (Statement 7) ... | | | | 100 | 0 | 0 |
| 39 | SURPLUS FOR YEAR, per Balance Sheet ... ... | | | | 175 | 19 | 11 |
| £2226 | | | | | £2359 | 10 | 6 |

## INCOME

| 1953<br>£ | | £ | s. | d. | £ | s. | d. |
|---|---|---|---|---|---|---|---|
| | ANNUAL SUBSCRIPTIONS RECEIVABLE: | | | | | | |
| 1383 | Received for 1954 ... ... ... ... | 1390 | 12 | 2 | | | |
| 275 | Received for previous years ... ... ... | 194 | 1 | 6 | | | |
| 230 | *Add* Arrears at 31 December 1954 £808 3 6<br>Estimated to realise ... ... ... ... | 250 | 0 | 0 | | | |
| 1888 | | 1834 | 13 | 8 | | | |
| 200 | *Less* Arrears at 31 December 1953 £691 10 0<br>Estimated to realise ... ... ... ... | 230 | 0 | 0 | | | |
| 1688 | | | | | 1604 | 13 | 8 |
| | ADMISSION FEES RECEIVABLE: | | | | | | |
| 37 | Received for 1954 ... ... ... ... | 43 | 0 | 0 | | | |
| 4 | Received for previous years ... ... ... | 3 | 10 | 0 | | | |
| 4 | *Add* Arrears at 31 December 1954 ... ... | 2 | 10 | 0 | | | |
| 45 | | 49 | 0 | 0 | | | |
| 5 | *Less* Arrears at 31 December 1953 ... ... | 3 | 10 | 0 | | | |
| 40 | | | | | 45 | 10 | 0 |
| | ROYAL SOCIETY GRANT: | | | | | | |
| | 1953 Balance ... ... ... ... ... ... | 50 | 0 | 0 | | | |
| 250 | 1954 ... ... ... ... ... ... | 300 | 0 | 0 | | | |
| | | | | | 350 | 0 | 0 |
| 248 | PUBLICATIONS SALES ... ... ... ... | | | | 259 | 6 | 10 |
| | TRANSFER FROM ILLUSTRATIONS FUND (Statement 6) | | | | 100 | 0 | 0 |
| £2226 | | | | | £2359 | 10 | 6 |

# FUNDS FOR SPECIAL PURPOSES

## BEQUESTS FUND

Statement 3

| | £ | s. | d. | | £ | s. | d. |
|---|---|---|---|---|---|---|---|
| Balance, 31 December 1954 (per Balance Sheet) ... ... ... | 306 | 8 | 5 | Balance, 1 January 1954 ... ... ... ... ... ... ... | 282 | 4 | 2 |
| | | | | Balance of Legacy not Invested—Prof. W. E. Skeats ... ... ... | 2 | 7 | 9 |
| | | | | Investment Income (Statement 12) ... ... ... ... ... | 21 | 16 | 6 |
| | £306 | 8 | 5 | | £306 | 8 | 5 |

## CENTENARY FUND

Statement 4

| | £ | s. | d. | | £ | s. | d. |
|---|---|---|---|---|---|---|---|
| Balance, 31 December 1954 (per Balance Sheet) ... ... ... | 40 | 13 | 1 | Balance, 1 January 1954 ... ... ... ... ... ... ... | 5 | 13 | 1 |
| | | | | Investment Income (Statement 12) ... ... ... ... ... | 35 | 0 | 0 |
| | £40 | 13 | 1 | | £40 | 13 | 1 |

## COMPOUNDING FUND

Statement 5

| | £ | s. | d. | | £ | s. | d. |
|---|---|---|---|---|---|---|---|
| Balance, 31 December 1954 (per Balance Sheet) ... ... ... | 71 | 15 | 10 | Balance, 1 January 1954 ... ... ... ... ... ... ... | 296 | 13 | 2 |
| Purchase of £300 3½% Treasury Stock ... ... ... ... ... | 282 | 2 | 0 | Investment Income (Statement 12) ... ... ... ... ... | 57 | 4 | 8 |
| | £353 | 17 | 10 | | £353 | 17 | 10 |

# Funds for Special Purposes (*Continued*)

## ILLUSTRATIONS FUND

### Statement 6

| | £ | s. | d. | | £ | s. | d. |
|---|---|---|---|---|---|---|---|
| Balance, 31 December 1954 (per Balance Sheet) … … … … | 22 | 18 | 7 | Balance, 1 January 1954 … … … … … … … | 72 | 11 | 1 |
| Transfer to Income and Expenditure Account … … … … | 100 | 0 | 0 | Investment Income (Statement 12) … … … … … | | 12 | 6 |
| | | | | Donations and Subscriptions … … … … … … | 49 | 15 | 0 |
| | £122 | 18 | 7 | | £122 | 18 | 7 |

## INDEXING FUND

### Statement 7

| | £ | s. | d. | | £ | s. | d. |
|---|---|---|---|---|---|---|---|
| Balance, 31 December 1954 (per Balance Sheet) … … … | 121 | 13 | 10 | Balance, 1 January 1954 … … … … … … … | 141 | 2 | 3 |
| Cost of Index … … … … … … … … … | 119 | 8 | 5 | Transfer from Income and Expenditure Account … … … | 100 | 0 | 0 |
| | £241 | 2 | 3 | | £241 | 2 | 3 |

## WATTS CHARNWOOD FOREST FUND

### Statement 8

| | £ | s. | d. | | £ | s. | d. |
|---|---|---|---|---|---|---|---|
| Balance, 31 December 1954 (per Balance Sheet) … … … | 150 | 11 | 0 | Balance, 1 January 1954 … … … … … … … | 135 | 10 | 6 |
| | | | | Sales of Books … … … … … … … … | 15 | 0 | 6 |
| | £150 | 11 | 0 | | £150 | 11 | 0 |

# TRUST FUNDS

## FOULERTON AWARD FUND

Statement 9

| | £ s. d. | | £ s. d. |
|---|---|---|---|
| Award to Mr. H. Taylor ... ... ... ... ... ... ... | 10 0 0 | Balance, 1 January 1954 ... ... ... ... ... ... ... | 26 6 1 |
| Balance, 31 December 1954 (per Balance Sheet) ... ... ... | 26 15 9 | Investment Income (Statement 12) ... ... ... ... ... | 10 9 8 |
| | £36 15 9 | | £36 15 9 |

## G. W. YOUNG GEOLOGICAL INVESTIGATION FUND

Statement 10

| | £ s. d. | £ s. d. | | £ s. d. |
|---|---|---|---|---|
| Income Tax Repaid to Public Trustee ... ... ... ... ... | | 3 15 10 | Balance, 1 January 1954 ... ... ... ... ... ... ... | 81 6 7 |
| Grants: | | | | |
| Mr. H. Spencer ... ... ... ... ... | 10 0 0 | | | |
| Mr. R. Milbourne ... ... ... ... ... | 25 0 0 | | | |
| | | 35 0 0 | | |
| Balance, 31 December 1954 (per Balance Sheet) ... ... ... | | 42 10 9 | | |
| | | £81 6 7 | | £81 6 7 |

## HENRY STOPES MEMORIAL FUND

Statement 11

| | £ s. d. | | £ s. d. |
|---|---|---|---|
| Balance, 31 December 1954 (per Balance Sheet) ... ... ... | 29 10 9 | Balance, 1 January 1954 ... ... ... ... ... ... ... | 21 11 2 |
| | | Investment Income (Statement 12) ... ... ... ... ... | 7 19 7 |
| | £29 10 9 | | £29 10 9 |

Statement 12

## SCHEDULE OF INVESTMENTS — 31 DECEMBER 1954

| | AT COST OR VALUE WHEN ACQUIRED | | INVESTMENT INCOME (GROSS) | |
|---|---|---|---|---|
| | £ s. d. | £ s. d. | £ s. d. | £ s. d. |
| FUNDS FOR SPECIAL PURPOSES: | | | | |
| Bequest Fund: | | | | |
| £143 8 9 3½% War Stock ... ... | 141 14 0 | | 5 0 6 | |
| £150 New Zealand 3½% Stock 1960/64 | 122 5 0 | | 5 5 0 | |
| £285 3% Defence Bonds ... ... | 285 0 0 | | 8 11 0 | |
| £100 3% Savings Bonds 1960/70 ... | 100 0 0 | | 3 0 0 | |
| £441 5 4 3% British Transport Stock 1978/88 ... ... ... ... | 400 0 0 | | – – – | |
| | | 1048 19 0 | | 21 16 6 |
| Centenary Fund: | | | | |
| £1000 3½% Defence Bonds ... ... | | 1000 0 0 | | 35 0 0 |
| Compounding Fund: | | | | |
| £1217 2 6 Nottingham Corporation 3% Irredeemable Stock ... ... | 1152 13 2 | | 36 10 2 | |
| £200 3% Savings Bonds 1955/65 ... | 200 0 0 | | 6 0 0 | |
| £170 3½% War Stock ... ... ... | 152 14 5 | | 5 19 0 | |
| £100 3% Savings Bonds 1965/75 ... | 100 0 0 | | 3 0 0 | |
| £300 3½% Treasury Stock 1977/80 ... | 282 2 0 | | 5 15 6 | |
| | | 1887 9 7 | | 57 4 8 |
| Illustrations Fund: | | | | |
| £21 0 10 Metropolitan Water Board 3% "B" Stock ... ... ... ... | | 20 0 0 | | 12 6 |
| TRUST FUNDS: | | | | |
| Foulerton Award Fund: | | | | |
| £349 7 0 3% British Transport Guaranteed Stock 1978/88 ... ... ... | | 294 11 0 | | 10 9 8 |
| Henry Stopes Memorial Fund: | | | | |
| £265 19 2 Government of Newfoundland 3% Stock 1943/63 ... ... ... | | 260 12 9 | | 7 19 7 |
| TOTAL INVESTMENTS, per Balance Sheet ... ... | | £4511 12 4 | | |

MARTIN, FARLOW & CO., *Incorporated Accountants.*

We have compared these Statements with the books and records presented to us and find them to agree.

We have also verified the Investments and Cash Balances held by the Association at 31 December 1954.

L. J. PITT, *Treasurer.*

D. V. AGER } *Auditors*
A. G. DAVIS

## PUBLICATIONS

**Publications Committee.** The committee consisted of the seven officers. Mrs. J. M. Eyles, and Messrs. E. E. S. Brown, T. Eastwood, A. F. Hallimond, G. W. Himus and H. Dighton Thomas. Dr. A. J. T. Dollar succeeded Mr. C. D. Ovey, who resigned from the office of Editor during the year, and Dr. M. K. Wells became Secretary of the Committee in place of Dr. W. E. Swinton, who also resigned.

The Committee met on six occasions and considered twenty-three papers on which reports were made to Council.

**Proceedings.** Three parts of Volume 65 were published during the year. The number of pages was 312 (compared with 316 for all four parts of Volume 64), and there were nine plates.

## MEETINGS

Nine Ordinary Meetings were held at which eight papers were read and four papers were 'taken as read'.

The thanks of the Association are due to the authors of papers and to the Geological Society for the use of its Apartments throughout the year.

## REUNION

The Annual Reunion was held at Chelsea Polytechnic on Saturday, 6 November. Many interesting exhibits were shown and it was attended by over 300 members and friends.

Thanks are due to the Principal and staff of the Polytechnic and the members concerned.

## FIELD MEETINGS

The Committee consisted of the Officers, Mrs. H. K. Hawkes, Mrs. E. M. Evans, and Messrs. J. F. Hayward, J. F. Kirkaldy, Vernon Wilson, B. Ainsley, D. Curry, A. G. Davis and W. E. Smith.

During the year there were five Demonstrations, two week-end, five whole day and five half day Field Meetings. Easter and Whitsun Field Meetings were held in the Birmingham and Shaftesbury areas respectively. The Lake District and Italy were visited for the Summer Long Field Meetings.

The thanks of the Association are due to the Directors and all others who organised and assisted at these meetings.

## THE LIBRARY

The Library Committee consisted of the President, Mrs. V. A. Eyles, Mrs. H. K. Hawkes, and Messrs. R. Bradshaw, R. Reeley, C. D. Ovey, R. V. Melville and J. Wilkes, Librarian of University College.

The Association acknowledges with thanks the gifts of books and pamphlets listed in the Sessions Report.

Exchange of publications has been instituted with the following:

Geological Society of Japan;
Kyushu University, Japan;
British Glaciological Society;
Geoloski Zavod, Ljubliana, Yugoslavia.

## NORTH-EAST LANCASHIRE GROUP

Chairman: J. Ranson, A.M.I.M.E., F.G.S.

Secretary: D. H. Learoyd, B.SC., F.G.S.

Committee: J. E. Carter, G. F. Urry, S. Westhead and I. A. Williamson.

During the year six meetings were held and there were four field meetings. Particulars are published in the Report of the Session. Thanks are due to the Authorities of the Blackburn Technical College for the use of rooms.

## MIDLAND GROUP

Chairman: A. Ludford, M.SC., F.G.S.

Secretary: Miss Grace M. Bauer.

Committee: N. Howell, I. Strachan, A. F. Archer, D. R. Hughes.

During the year five meetings were held in the Geology Department, The University, Birmingham, and there were six field meetings. Particulars are published in the Report of the Session. Thanks are due to Professor Shotton for the use of the Geology Department at the University for meetings.

## NORTH STAFFORDSHIRE GROUP

Chairman: J. C. Parrack, B.SC., F.R.G.S.

Secretary: T. S. Purcell, B.SC.

Treasurer: J. T. Gleaves, B.A.

Field Secretary: J. Myers, B.SC., F.G.S., F.R.G.S.

Research Group Secretary: D. O. Thomas.

Committee: W. J. Adams, E. Berrer, Prof. F. Wolverson Cope, T. S. Jones, P. S. Keeling, J. T. Wattison, E. A. Watkin.

During the year eight meetings were held and there were four field meetings. Details are published in the Report of the Session. Thanks are due to the Authorities of the Arts Centre for the use of rooms.

## TRUSTEES

The Trustees of the Association for 1954 were:

*Managing:* Mr. S. Hazzledine Warren, F.G.S., Dr. W. F. Fleet, M.SC., A.R.I.C., A.C.P., F.G.S., and Mr. E. C. Martin, O.B.E., B.SC., A.R.I.C., F.G.S.

*Custodian:* The Royal Bank of Scotland, Western Branch.

## FOULERTON AWARD

The Foulerton Award for the year was given to Mr. H. E. Taylor in recognition of his services to Geology and the Association.

## HOUSE LIST

Professor David Williams retires as Senior Vice-President and Messrs. B. Ainsley, C. D. Ovey and Mrs. H. K. Hawkes as Ordinary Members of Council. Mr. R. Reeley resigns as General Secretary at his own request. Thanks are due to these members for services rendered to the Association.

## REPORT OF THE SESSION 1954

**Ordinary Meeting,** 8 *January* 1954. G. W. Himus, Ph.D., F.G.S., President, in the chair.

Abdul Sahib Alwan, Donald Archibald Campbell, F.R.A.S., Horace Edward Dall, Joakim Jalmar Donner, R. T. Fowler-Farkas, Paul William Miller, David Samuel Rawson, John George Shotter, Christopher Gerard Wakeman and Richard Gilbert West were elected members of the Association.

Dr. Gilbert Wilson and Mr. D. V. Ager were elected Auditors of the accounts for 1953.

The following papers were read: (1) 'The volcanic and associated rocks of Giffard Bay, Jersey, C.I.', by Miss M. Casimir & F. A. Henson, B.Sc., F.G.S., and (2) 'The origin of aplites, with special reference to those of Jersey, C.I.', by A. K. Wells, D.Sc., F.G.S. & A. C. Bishop, B.Sc., F.G.S.

**Ordinary Meeting,** 5 *February* 1954. G. W. Himus, Ph.D., F.G.S., President, in the chair.

Miss Doris N. Allen, D. Blakeway, Miss Joan Mary Bull, Miss Bessie Caroline Bunting, Clifford George Burridge, Frederick Arthur Haverson, James Kidd, Miss Esther Kiddie, L. Lancaster, A.M.I.B.E., F.R.Met.S., Fuad Olumide Okunnu, John Victor Ross, B.Sc., A.R.C.S., F.G.S., Thomas George Wickens and Frederick Maurice Densumbe Yeo were elected members of the Association.

The following papers were taken as read: (1) 'A temporary exposure in the Bracklesham Beds near Sopley, Hants', by P. E. Fairbairn, B.A., B.Sc., A.R.S.M., F.G.S., and (2) 'A series of loessic deposits in the fifty-ft. terrace post-dating the main coombe rock of Baker's Hole, Northfleet, Kent', by J. P. T. Burchell.

The following paper was read: 'The southern margin of the Cairnsmore of Fleet granite at the Clints of Dromore, Galloway', by F. G. H. Blyth, Ph.D., M.Sc., F.G.S.

**Annual General Meeting,** 5 *March* 1954. G. W. Himus, Ph.D., F.G.S., President, in the chair.

The Annual Report of the Council was taken as read. It was moved by Mr. E. Evans, seconded by Mr. E. M. Venables, 'That the Report of the Council, including the Statement of Accounts, be adopted as the Annual Report of the Association for 1953'. The resolution was carried *nem. con.*

The President declared the following members duly elected as Officers and Members of Council in accordance with Rule XIII: *President*, L. R. Cox, M.A., SC.D., F.R.S., F.G.S.; *Vice-Presidents*, D. Williams, D.SC., Ph.D., B.E., F.G.S., A. J. Butler, O.B.E., M.SC., F.G.S., T. Eastwood, A.R.C.S., M.I.M.M., F.G.S., H. Dighton Thomas, M.A., Ph.D., F.G.S., G. W. Himus, Ph.D., F.G.S.; *Treasurer*, L. J. Pitt, F.G.S.; *Secretaries*, General—R. Reeley, F.G.S.; Field Meetings—S. W. Hester, F.G.S.; Publications Committee—W. E. Swinton, B.SC., Ph.D., F.G.S., F.M.A.; *Editor*, C. D. Ovey, B.SC., F.G.S., F.R.Met.S.; *Librarian*, R. Bradshaw, M.SC., F.G.S.; *Twelve other Members of Council*, B. Ainsley, F.G.S., Mrs. H. K. Hawkes, M.SC., F.G.S., A. F. Hallimond, M.A., SC.D., F.G.S., Mrs. V. A. Eyles, B.SC., F.G.S., E. C. Martin, O.B.E., B.SC., A.R.I.C., F.G.S., W. E. Smith, M.SC., F.G.S., D. Curry, M.A., F.G.S., S. Bracewell, B.SC., D.I.C., A.R.C.S., F.G.S., Gilbert Wilson, Ph.D., M.SC., D.I.C., F.G.S., Mrs. E. M. Evans, M.SC., F.G.S., Mrs. J. V. Harrison, M.A., B.SC., A. J. Dollar, B.SC., Ph.D., A.K.C., F.R.S.E., F.G.S.

It was moved by Mr. A. G. Bell, seconded by Dr. R. W. Pocock and duly carried, 'That the best thanks of the Association be given the retiring President, the Officers, retiring members of Council and the Auditors'.

The Foulerton Award was presented to Mr. Herbert E. Taylor, in recognition of his work for Geology and the Association. The President said:

> Herbert Taylor: Geological science in Great Britain owes much to the work of enthusiastic amateurs who, in spite of their preoccupation in other fields, delight in devoting their leisure hours to investigating their surroundings. Among this select band you are numbered, and it is the unanimous wish of Council that your labours shall be recognised by the Foulerton Award.
>
> You were drawn to the study of geology while still a schoolboy and your interest in the science has never flagged; you continued your studies at Chelsea Polytechnic under Dr. Maslen and helped to found there a Geological Field Club, of which you were Honorary Secretary for some years. As a teacher of science, you took the opportunity of inducting your pupils into the principles of geology, both in the classroom and by visits to museums.
>
> You have been a Member of the Geologists' Association for over forty years, have participated in many Field Meetings, exhibited at Reunions, and are a life member.
>
> For the past five years you have been carrying out specialised work on the London Clay in association with two previous recipients of the Foulerton Award, the late Arthur Wrigley and E. M. Venables. In particular, you have contributed to our knowledge of the Eocene serpulids by your discovery of

> an exposure yielding plentiful specimens of *Rotularia bognoriensis* which have contributed to our knowledge of the life-history of the creatures. Incidentally, the creature provided quite a useful contribution to our Illustrations Fund, a brisk sale of specimens having been promoted at the Reunion when the results of the investigation were exhibited.
>
> Since 1949 you have been working with E. M. Venables in developing his discovery of beetles in the London Clay. Together, you have found and placed on record a large suite of these fossils from Bognor Regis. Although not strictly micro-fossils, the specimens are small and require for their discovery not only keen and critical eyes, but the training and experience necessary to enable you to recognise the creatures. One wonders how many geologists have noted the presence of small black ovoid objects in the London Clay and rejected them as fragments of carbonised wood or nodules of pyrite and marcasite which were not worth further consideration.
>
> By no means the least of your virtues lies in the fact that you have placed the results of your work freely at the disposal of specialists and have supplied specimens to National Museums, and to museums of educational establishments, where they will be of maximum utility.
>
> As one of my last duties as President of the Association, it is with great pleasure that I ask you to accept this token of our regard, not merely as a recognition of past work, but in the confident hope that it will act as an incentive to you to continue investigations which have already proved so fruitful.

The President then delivered his address entitled 'The Association and its Field Meetings'.

It was moved by Dr. Gwyn Thomas, seconded by Mr. A. G. Davis, and duly carried, 'That the best thanks of the Association be accorded the President for his address'.

**Ordinary Meeting following Annual General Meeting.** L. R. Cox, M.A., SC.D., F.R.S., F.G.S., President, in the chair.

Kenneth William Barr, Ph.D., F.G.S., Eric Charles Frederick Bird, Miss Marie Corbett, B.SC., Chudamani Ratnam, B.SC. and Miss Enid Wheeler were elected members of the Association.

**Ordinary Meeting,** 2 *April* 1954. L. R. Cox, M.A., SC.D., F.R.S., F.G.S., President, in the chair.

John Anthony Eaton Allum, Norman Simpson Angus, Herbert S. Black, M.A., Mrs. Gloria Borley, James Dougherty, Alfred Kenneth De Denne, John Michael Hodgson, Percy Desmond Huss, Miss Diane Constance Judge, Miss Kathleen Mary Knight, B.SC., Anthony M. Leonard, John Pollock, James Gordon Samson, Edgar Howard Shackleton, F.G.S., Ronald Parke Wheatley, Harold E. Wilson, R. H. Wilson and John W. Wright were elected members of the Association.

The following paper was read: 'The geology of the Mere Fault', by B. H. Mottram, B.A.

**Ordinary Meeting,** 7 *May* 1954. L. R. Cox, M.A., SC.D., F.R.S., F.G.S., President, in the chair.

Joseph Alfred Alltoft, Brian William Avery, Miss Kathleen Entwisle, Miss Helen Augusta Hope Macdonald, Miss Marigold Elbra Alston Snaith and Michael J. Tulley were elected members of the Association.

The following papers were 'taken as read': (1) '*Falciferella*, a new genus of Gault Ammonites, with a review of the family Aconeceratidae in the British Cretaceous', by R. Casey, F.G.S., and (2) 'The gault at Greatness Lane, Sevenoaks, Kent', by R. A. Milbourne.

The following paper was read: 'The Banff Nappe: an interpretation of the structure of the Dalradian Rocks of North-East Scotland', by Professor H. H. Read, D.SC., A.R.C.S., F.R.S., F.G.S.

**Ordinary Meeting,** 11 *June* 1954. L. R. Cox, M.A., SC.D., F.R.S., F.G.S., President, in the chair.

John Howland Campbell, Alan Albert Clare, Eric Ferdinand William Dux, Syed Manzurul Hasan, M.SC., F.G.S., William Mason Russell Paterson, Arthur Fred Eric Riley, Miss Isabel L. Scott-Elliot, Isles Strachan and David L. Woolf were elected Members of the Association.

The following paper was read: 'The Moine Thrust: its discovery, age and tectonic significance', by Donald B. McIntyre, Ph.D., D.SC., F.R.S.E., F.G.S.

**Ordinary Meeting,** 2 *July* 1954. L. R. Cox, M.A., SC.D., F.R.S., F.G.S., President, in the chair.

John Stewart Buchanan, Maurice Wylde Carter, Thomas Roy Dobson, Kenneth Charles Ford, Gerald James Spurgeon Govett, Anthony Thomas Grimes, Marek Andrzej Jerzy Piasecki, Roy Neville Sheridan, Nicholas Stephens, Thimmaiah Thimmaiah, B.SC., George Richard Tidman, John Richard Daniel Tidmarsh, Geoffrey Reginald Tresise and Brian James Walton were elected members of the Association.

The following paper was read: 'Piedmont Profiles in the Arid Cycle', by W. G. V. Balchin, M.A., Ph.D., F.R.G.S., F.R.Met.S., & Norman Pye, B.A., F.R.G.S., F.R.Met.S.

**Ordinary Meeting,** 6 *November* 1954. L. R. Cox, M.A., SC.D., F.R.S., F.G.S., President, in the chair.

Ronald John Firman, Ph.D., and Miss Freda Elsie Warman were elected members of the Association.

The Reunion which followed was held at Chelsea Polytechnic and was attended by over 300 members and friends. (For list of exhibits, see page 148.)

**Ordinary Meeting,** 3 *December* 1954. L. R. Cox, M.A., SC.D., F.R.S., F.G.S., President, in the chair.

Graham John Baskerville, Malcolm Leslie Bickley, Mrs. Hannah Bone, Henry Dronfield Brook, Peter Ronald Bush, Peter Campbell, Anthony Michael John Kent Clarke, Miss Margaret Anne Crowther, John Brian Dalrymple, John Docherty, Anthony Meredith Evans, Brian Michael Funnell, Maxwell Roland Gillespie, Frank Gosling, John Trevor Greensmith, B.SC., F.G.S., Miss Constance Patricia Griffiths, Anthony Hallam, John Hampton, Mrs. Ethel W. Hart, Sam Tak Hin, William Andrew Hodgson, Miss Marion Johnson, Robert Hermon Jones, Michael Samuel Lewis, Richard Malden, Bernard Meltzer, B.SC., Ph.D., William Stewart Moffat, B.SC., Robin Nicholson, Christopher John Pallant, Robert Christopher Plowright, Dennis Albert Preddy, Norman Pye, B.A., F.R.G.S., F.R.Met.S., Francis Noel Radford, Miss Edith Starkey Richardson, Peter Laurence Siems, John James Anthony Taylor, Mrs. Daphne Marjorie Weaver, George Albert Wells, M.A., Ph.D., and Herbert Arthur White were elected members of the Association.

The following paper was read: 'The Deposition of the Upper Dalradian Rocks of the Banffshire coast', by John Sutton, Ph.D., F.G.S., & Janet Watson, Ph.D., F.G.S.

## LIST OF EXHIBITS

**British Museum (Natural History)**

*Department of Geology:*

(*a*) Some unusual Liassic Brachiopods from the Middle Atlas Mountains, Morocco. Dr. H. M. Muir Wood.
(*b*) *Pteraspis dunensis* from the Eifel. H. A. Toombs.

*Department of Mineralogy:*

(*a*) Rocks from Carabaya, Departamento de Puna, Peru, collected by G. H. Francis, 1954.
(*b*) New meteorites from Pakistan and Saudi Arabia.
(*c*) Crystal model of epidote.

**Geological Survey and Museum**

(*a*) Specimens and diagrams illustrating the geology of the Upton, Burford (1952–3) Borehole. (Palaeontological Department.)
(*b*) Gemstones recently added to the Museum Collections.
(*c*) Selected specimens from five lead-zinc mining districts, recently presented to the Museum.
(*d*) New publications.

**Ager, D. V., J. Sutton and M. L. Larman**

Specimens collected on the Summer Field Meeting in Italy.

**Barron, R. S. (Dauntsey's School)**

Geology around Ashover, specimens and maps.

**Bottley, E. P.**

(*a*) Minerals and rocks from the Island of Vulcano, Aeolian Islands.
(*b*) The Bottley–White Mineral and Rock Pulveriser for analyses.
(*c*) The Mineral Stichtite, fine rough specimens and cut as a gemstone.

**Brown, Miss M. M.**

A fauna from the upper sandy London Clay of Oxshott, Surrey.

**Campbell, D. A.**

Deep Sea Dredging Samples.

**Carreck, J. N. and M. P. Kerney**

Quaternary mammalian and molluscan remains from the Brickearths of Tankerton Bay, Whitstable, Kent.

**Casey, R.**

Specimens illustrating the ammonite succession in the Lower Greensand of the Isle of Wight.

**Casey, R. and R. A. Milbourne**

The ammonite *Falciferella*.

**Cutrock Engineering Co. Ltd.**

(*a*) Rock cutting and grinding machine, G.F.3;
(*b*) Rock splitting machine, 8 ton capacity;
(*c*) Two Stereometers;
(*d*) Geological hammers and augers.

**Dollar, A. J. and B. C. Hicks**

A microscope furnace for thermal analysis up to a temperature of 1600°C.

**Dollar, A. J. and F. J. Fitch**

The detection of rock junctions by radioactivity measurements: some results.

**Fagg, C. C.**

Drawings and relief models to illustrate the coombes and embayments of the Chalk Escarpment.

**Hallimond, A. F.**

Specimens collected during the Summer Field Meeting in Italy.

**Martin, E. R.**

Simple home-made inexpensive gadgets useful in surveying, to estimate distances on the 'flat', heights and dips, as well as a method for compactly storing small fossils.

**Marston, A. T.**

'Piltdown, 1953–4. British Museum (Natural History) excuses debunked.'

**Moore, E. W. J.**

Series of goniatities from the so-called Yoredale Shales of Ireland, including a suite of specimens of *Goniatites striatus* to show development and variation in this species.

**Myers, J. (Wolstanton County Grammar School)**

Note books of sixth-form pupils and specimen of *Glyphea* from the Lower Oxford Clay, Crookhill Brickyard, near Weymouth.

**Oakley, K. P. and L. E. Parsons**

Specimens illustrating Piltdown Man, now defunct.

**Reekie, J. (Royal Liberty School)**

Records of field excursions with examples of collections by individual boys.

**Venables, E. M. and H. E. Taylor**

Fossils from the London Clay of Bognor.

**Wells, A. K.**

(*a*) Scenery of the western fjords of Norway.
(*b*) Granite-diorite relationship at Ronez, Jersey, C.I.

**Whitten, D. G. A., G. T. Raine and Students of Geology Section, Kingston Technical College**

Scottish Minerals.

**Wilson, Gilbert**

Specimens and photographs from the Type area of the Moine Series, A'Mhoine, Sutherland.

**Wright, C. W.**

(*a*) Phylogeny of the Desmocerataceae.
(*b*) Recent acquisitions.

## FIELD MEETINGS 1954

The following field meetings and demonstrations took place:

22 *January*. Visit to the Geological Survey and Museum, South Kensington, at the invitation of the Director, Dr. W. J. Pugh, F.R.S.

20 *February*. Visit to the Mineralogy Department of the British Museum (Natural History), South Kensington, at the invitation of the Keeper of Minerals, Dr. G. F. Claringbull.

27 *March*. Demonstration of some of the building stones of Kensington and Westminster by S. E. Ellis.

16–19 *April*. Easter Field Meeting in the Birmingham area. Director, Professor F. W. Shotton.

24 *April*. Demonstration at the Shell Training Centre, Teddington, by A. E. Gunther.

9 *May*. Field Meeting at Pegwell Bay. Directors, Dr. W. S. Pitcher and D. J. Shearman.

15 *May*. Field Meeting at Brentwood. Director, F. A. Middlemiss.

23 *May*. Field Meeting at Worthing. Director, E. C. Martin.

5–8 *June*. Whitsun Field Meeting in the Shaftesbury District. Director, B. H. Mottram.

19 *June*. Visit to the Geological Islands at the Crystal Palace. Director, Dr. W. E. Swinton.

11 *July*. Field Meeting at the Isle of Sheppey. Directors, G. F. Elliott and A. G. Davis.

17 *July*. Visit to Ashdown No. 1 well near Crowborough. Director, R. G. Brunstrom.

31 *July*–1 *August*. Week-end Field Meeting in the Rugby District. Directors, Professor F. W. Shotton, Dr. Vernon Wilson and R. H. Hoare.

8 *August*. Field Meeting at Wrabness, Essex. Director, Dr. J. F. Hayward.

28 *August*. Field Meeting at Oxshott. Director, Miss M. M. Brown.

4–11 *September*. Summer Field Meeting (i) in the Lake District. Organising Director, Professor S. E. Hollingworth, Assistant Directors, Dr. R. J. Firman, Professor W. B. R. King, F.R.S., Dr. G. H. Mitchell, F.R.S., Dr. R. L. Oliver, W. C. C. Rose and Dr. F. M. Trotter.

11 *September*. Field Meeting at Borough Green and Ightham, Kent. Directors, J. N. Carreck and R. Casey.

15–30 *September*. Summer Field Meeting (ii) in Italy. Director, Dr. A. Azzaroli.

25 *September*. Field Meeting at Sevenoaks. Director, R. A. Milbourne.

2–3 *October*. Week-end Field Meeting in the Yeovil district. Directors, Dr. Vernon Wilson and G. F. G. Worraker.

4 *December*. Demonstration at the Road Research Laboratory, Harmondsworth, by Dr. T. Lonsdale.

## NORTH-EAST LANCASHIRE GROUP

The following meetings and field meetings were held:

29 *January*. Lecture: 'The Yorkshire coast', by E. Pilling.

26 *February*. Chairman's Address: 'The scenery and geology of Ingleborough', by J. Ranson, A.M.I.Min.E., F.G.S.

26 *March*. Lecture: 'Some features of the geology of Colorado, Arizona and New Mexico', by Dr. D. Parkinson, F.G.S.

22 *May*. Field Meeting: The Grit Succession and glacial features north-east of Horwich. Leader, D. H. Learoyd, B.SC., F.G.S.

5–8 *June*. Long Field Meeting: Dufton, Appleby. Leader, D. C. S. Hutchinson.

26 *June*. Field Meeting: Glacial overflow at Harcles Hill; post-glacial gorge of R. Irwell at Brooksbottom and River Terraces at Summerseat. Leader, J. Ranson, A.M.I.Min.E., F.G.S.

28 *August*. Field Meeting: The Pennine Anticline. Leaders, I. A. Williamson and K. L. Ashworth.

25 *September*. Field Meeting: The Grit Succession and Glacial overflows near Wheelton. Leader, G. F. Urry.

29 *October*. Annual General Meeting, with symposium of résumés on the Field Meetings.

26 *November*. Lecture: 'Geology of the country around Appleby', by D. C. S. Hutchinson.

10 *December*. Lecture: 'Geology and mining history of Thieveley and Rimington lead mines, by I. A. Williamson.

## MIDLAND GROUP

The following meetings and field meetings were held:

30 *January*. Lecture: 'Some features of the geology of Colorado, Arizona and New Mexico', by Dr. D. Parkinson, F.G.S.

27 *February*. Lecture: 'Island of Gotland', by H. Sanders.

7–9 *May*. Field Meeting: Woolhope Area. Leaders, Rev. B. B. Clarke and Dr. J. D. Lawson.

29 *May*. Field Meeting: Lickey area. Leader, W. G. Hardie.

20 *June*. Field Meeting: Charnwood Forest. Leader, A. Ludford.

10 *July*. Field Meeting: The Wrens Nest, Dudley. Leader, A. Ludford.

22 *August*. Field Meeting: Habberley and Trimpley. Leaders, G. Cotton and W. Waldron.

18 *September*. Field Meeting: Weston Alabaster Works, nr. Stafford, and Tutbury Plaster Works. Leader, A. Bray.

16 *October*. Lecture: 'Checking crystals with camera and microscope', by A. J. Aiers.

13 *November*. Lecture: 'The Old Red Sandstone of the Merbach Ridge, Herefordshire, with an account of the Middlewood Sandstone, a new fossiliferous horizon there, 500 ft. below the *Psammosteus* Limestone', by the Rev. B. B. Clarke.

11 *December*. Exhibition of coloured slides, by Professor F. W. Shotton and Messrs. Parrack, Aiers, Strachan and Hardie.

## NORTH STAFFORDSHIRE GROUP 1954

14 *January*. Lecture: 'The geology of the Isle of Wight', by J. Myers, B.SC., F.R.G.S., F.G.S.

11 *February*. Lecture: 'Gemstones', by V. A. Dembo, B.SC.

11 *March*. Annual General Meeting. Chairman's Address by J. C. Parrack, B.SC., F.R.G.S.: 'Some aspects of glaciation.'

8 *April*. Lecture: 'The history of geological research in the Weald', by J. F. Kirkaldy, D.SC., F.G.S.

13 *May*. Research Group Directors' Evening: Prof. F. W. Cope, D.SC., F.G.S.; P. S. Keeling, B.SC., F.R.I.C., A.R.S.M.; J. Myers, B.SC., F.R.G.S., F.G.S.

21–23 *May*. Field Meeting to Cheltenham District. Leader, J. Myers, B.SC., F.R.G.S., F.G.S.

20 *June*. Field Meeting to Charnwood Forest: Leader, Dr. W. W. Black, F.G.S.

11 *July*. Field Meeting to View Edge and Onibury: Leader, J. T. Wattison, F.G.S.

19 *September*. Field Meeting to Ashover: Leader, T. S. Jones, F.G.S.

14 *October*. Annual Conversazione: short talks by Dr. F. Moseley, F.G.S., J. Myers, B.SC., J. C. Parrack, B.SC., J. T. Wattison, F.G.S.

11 *November*. Visit to the Geology Department, University College of North Staffordshire, at the invitation of Prof. F. Wolverson Cope, D.SC., F.G.S.

9 *December*. Lecture: 'Astronomy and Geology', by C. D. Grimwade. During the year, J. Myers, B.SC., F.R.G.S., F.G.S., Field Secretary, was awarded the Spanton Medal of the North Staffordshire Field Club, for services to Geology in North Staffordshire and district.

## DONATIONS TO THE LIBRARY

ARKELL, W. J. 'A palaeolith from Sherborne.' *Dorchester*, 1954; 'Two Jurassic Ammonites from South Island, New Zealand, and a note on the Pacific Ocean in the Jurassic.' *New Zealand*, 1953; 'Geology and prehistory from the train, Oxford–Paddington.' *Oxford*, 1945; 'Palaeoliths from the Wallingford Fan-Gravels.' *Oxford*, 1945; 'The building stones of Blenheim Palace, Cornbury Park, Glympton Park and Heythrop House, Oxfordshire.' *Oxford*, 1948.

BEAN, R. T. 'Relation of gravity anomalies to the geology of central Vermont. . . .' *Rochester*, N.Y., 1953.

BULLEN, K. E. 'Seismology.' *London*, 1954.

CUMMINGS, R. H. 'Developments in micropalaeontological technique.' *Chicago*, 1952. '*Saccaminopsis* from the Silurian.' *Colchester*, 1952.

DOUGLAS, J. A. 'A new structure in the Forest Marble of Oxford.' *Oxford*.

DUNNINGTON, H. V. 'Stylolite development post-dates rock induration.' *Tulsa*, Oklahoma, 1954.

EDMUNDS, F. H. 'British regional geology. The Wealden district.' *London*, 1954.

FAESSLER, C. 'Exercises en projection stereographique.' *Quebec*, 1953.

GEOLOGICAL SURVEY OF GREAT BRITAIN. Knox, 'Economic Geology of Fife Coalfields. Area 3.' *Edinburgh*, 1954.

GEOLOGICAL SURVEY OF GREAT BRITAIN. 'British regional geology. East Anglia and adjoining areas.' 3rd edition. *London*, 1954.

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## OBITUARY NOTICES, 1954

HERBERT ARTHUR BAKER was born on 16 May 1885 and died 6 December 1954. He obtained a teaching diploma in 1908 and graduated in science at University College, London, in the same year. He was employed in the

London Teaching Service until the outbreak of the First World War when he enlisted in the Royal Flying Corps. Later he was transferred to the Royal Navy in which he served until the end of hostilities. Between 1918 and 1920 he carried out research work at the Imperial College of Science and gained an M.SC. degree in 1919, and D.SC. and D.I.C. in 1920. In the same year he joined the Colonial Service and was appointed Government Geologist to the Falkland Islands. His report on these investigations remains the most comprehensive account of the geology of the Islands. In 1922 he returned to England and later in the same year took up employment as Headmaster of the Boys Secondary School at Grenada (British Windward Islands).

In the following year he was appointed Director of Education for that Colony. In 1926 he gave up this post to become Director of the Geological Survey of Newfoundland. He retained this appointment until the Government crisis of 1929 when he returned to England and re-entered the teaching profession. He remained in the latter until his retirement in 1950.

Dr. Baker's published work covered a wide range of geological topics. His paper on the 'Mechanical constitution of sediments', published in the *Geological Magazine* for 1920, is probably the most detailed paper published on the application of the method of elutriation to the study of arenaceous sediments, and his paper on 'Quartzite pebbles of Oldhaven age' in the same volume is an important contribution to the geology of the Tertiary beds of the London Basin. Underground geology was Dr. Baker's main interest, however, and he was a pioneer in the construction of underground contour and isopachyte maps from boring data. His last published work, 'An undiscovered coalfield. Probability of its existence beneath North Kent, the Thames Estuary and South East Essex', published in the *Iron and Coal Trades Review* for 1935 is an excellent example of the application of these methods to problems of economic geology in this country.

In the educational field Dr. Baker will be remembered as a thorough and genial teacher. He was keenly interested in the teaching of geology and physics, and his patience produced good results with even the dullest pupils.

Dr. Baker joined the Geologists' Association in 1909. He leaves a widow and one son.

S.J.P.

HERBERT FREDERICK BARKE died suddenly at Bristol on 31 March 1954, at the age of seventy-six. By profession a chemist, he was a Fellow of the Institute of Chemistry and served with the firm of Messrs. Cook and Barke in Bristol and Bath, as a public analyst, from about 1925 until his retirement in 1951.

He was a keen and active member of the Bristol Naturalists' Society, taking an especial interest in the Geological Section. A keen field investigator, he worked with many noted Bristol geologists including Arthur Vaughan, S. H. Reynolds and J. W. Tutcher who in their many published works gave well-deserved praise to his careful and detailed collecting. Barke was one of the earlier school of naturalists who loved and understood the whole countryside and rather shunned specialisation. Few matters of natural history escaped his keen powers of observation. It was a joy to accompany him in the field. A somewhat brusque manner belied his intense kindness and loyalty to his friends.

He became a member of the Geologists' Association in 1920, and is survived by his widow. F.S.W.

**WILLIAM SAVAGE BOULTON** was born at Old Swinford near Stourbridge in 1867. On leaving school he was an assistant to Lapworth for a short time, but on the latter's advice he went to study under Professor J. W. Judd at the Royal College of Science. Here he had a brilliant career which was prolonged for a further year in order to study advanced Zoology under Professor Howes and stellar spectroscopy under Professor, later Sir Norman, Lockyer.

In 1890 he returned to Mason's College, Birmingham, to act as Assistant Lecturer and Demonstrator to Professor Charles Lapworth. He worked here for seven years, absorbing ideas on teaching and research methods which he made good use of when he transferred to Cardiff as lecturer in geology and geography, and which he carried forward when, in 1913, he was appointed to succeed Lapworth at the University of Birmingham. At both places there was much need to stress the value and significance of geology in its application to problems of mining and engineering, and at Birmingham Lapworth had always emphasised this in his teaching. So it followed, perhaps almost instinctively, that Boulton became interested in applied geology and began to practise as a consultant on water supply and mining problems and as a technical witness in arbitration cases. As time went on he became recognised as one of the foremost geological consultants in the country, specialising in particular on underground water in the New Red rocks of the Midlands and in the Chalk of south-east England; but surface water supplies also claimed his attention and he advised on the geological aspects of a number of important impounding reservoir schemes. He carried on both types of work for many years after his retirement from the professorship at Birmingham in 1932.

What may be termed the 'applied science outlook' naturally coloured his teaching and led to the emphasis on field observation and mapping classes which characterised his syllabus both at Cardiff and at Birmingham, where he expanded and regularised the field classes that had been introduced by Lapworth as a complete innovation in geological instruction in the 1880's and '90's.

The same 'applied outlook' was responsible for his more important publications being on such subjects as the geological chapters in a six-volume 'Textbook of Practical Coal Mining' and his Presidential addresses and reviews that stressed the need for geological research in coal mining, the national importance of geological exploration and of a larger and better Geological Survey with the legal right of access to mining plans and bore-hole logs, etc., and of the potential value of a national fuel survey. It explains, too, why he was chosen to serve on such bodies as the Geological Survey Board, the Safety in Mines Research Board and the Government Inland Water Survey. I have pointed out above how this outlook dated back to Boulton's early contact with, and admiration of, Lapworth. He was in fact one of that small band (among whom one can recall Walcot Gibson, Hobley, Gilbert Cullis and Watts) who, fired by the genius of that great teacher, did so much to convert educated public opinion to a recognition of the value of geology as an indispensable servant of industry, mining and engineering, and to this end he developed the right type of teaching and research to produce the modern 'economic geologist'.

At Cardiff Boulton not only taught rapidly increasing numbers in the College, but in the towns of the coalfield he popularised the subject through his lectures for the University Extension Scheme.

In 1913 he was appointed to the Chair of Geology at Birmingham University, in succession to Professor Lapworth. He found the department, in a state of crippling division, operating for 'Applied Science Students' at the new University but for the 'Pure Science Students' in the old rooms and museum of Mason's College, three miles away in the centre of the town. After the war Boulton brought all the geological activities of his department under one roof at Edgbaston, and there he reorganised and expanded the teaching with great success. The Museum became one of the show-pieces at University functions and a valuable teaching tool at other times. It was during his professorship that the Geologists' Association held a week-end meeting at Birmingham in 1931, and he also acted as one of the leaders during the South Shropshire long excursion of 1925, but he joined the Association in 1907.

Boulton retired in 1932, on reaching the age-limit, after holding the Chair for nineteen years. He died from the after-effects of an accident in his eighty-eighth year. He will be remembered with gratitude and affection by past colleagues, and a host of old students, now scattered in many parts of the world.

L.J.W.

DAISY ELIZABETH HARVEY, who died 16 August 1954 at her residence, 33, De Vere Gardens, London, W.8, joined the Association in 1936. Educated at Royal Holloway College, she was trained as a teacher. During the First

World War she served in France with a nursing unit and afterwards as a translator. She attended several of the longer Field Meetings of the Association, and will be remembered by many for her engaging personality and generous disposition.

A.G.B.

IN HENRY GEORGE ALBERT HICKLING, Emeritus-Professor of Geology at King's College, Newcastle-upon-Tyne (University of Durham), Geology has lost a distinguished figure, and the College and University mourn a colleague of ripe experience and judgment. Born in Nottingham in 1883, he was educated there and in Angus, where, as he said to the writer, his future was determined by his rambles through a country that had known Lyell's hammer. Thereafter he became a student under Boyd Dawkins at Manchester; he was a distinguished graduate during a period of remarkable quality of students—within two or three years the department produced three future Fellows of the Royal Society. He was appointed Lecturer at Manchester in 1907 and Reader in 1917, having been for some time acting head of the department. In 1920 he was appointed to the J. B. Simpson Chair of Geology at Newcastle, from which he retired in 1948; he maintained his connection with the department most actively almost until his death.

Dr. Hickling came to Newcastle at a time of inflated classes, and was at considerable pains to improve the quarters and facilities of the department. In his last years as Professor he was to see his early problems surpassed by still more rigorous overcrowding, caused by a five-fold increase in the number of students taking geology. He excelled as a teacher; his deliberate delivery and clarity of thought ensured to his more elementary classes a sure grasp of principles, and his tireless enthusiasm with advanced students was directed towards an integration of the many aspects of geology. His conduct of field-classes was equally tireless; his slight figure belied his speed and endurance.

The early days in the Montrose area gave him an enduring interest in the Old Red Sandstone and its fossils, but it was at Manchester that he gave himself so largely to the study of Coal-Measure sedimentation and palaeobotany and to coalfield structure. His meticulous compilation of borehole, shaft, underground and surface data permitted him to make important contour-maps, e.g. of the surface of the Trencherbone seam in Lancashire, and much later of the Hutton seam of Durham. His several papers on the structure of fossil plants were excellent contributions to palaeobotany. At Newcastle he quickly became an authority on the geology of Northumberland and Durham, particularly of its coalfields. Here, too, he developed his work on coal-petrology with several research-students, notably Dr. B. N. Temperley and Dr. (now Professor) C. E. Marshall; and, with his colleague Dr. A. Raistrick developing the study of microspores at about the same time, the Newcastle department attained a world-wide reputation in coal-studies. Dr. Hickling also became a greatly respected authority on water-supplies; all who knew his work in this field must regret that he did not find the time to write a book on the geology of water. At Newcastle he fostered the geological activities of the Natural History Society of Northumberland, Durham and Newcastle-upon-Tyne, and devoted much time to the rearrangement and better display of the geological collection of the Society in the Hancock Museum; he was a member of the Council of the Society for nearly thirty years, and was largely responsible for the close liaison between King's College and the Museum.

Recognition of the value of his work has been widespread—for example, by the award of the Murchison Medal of the Geological Society of London in 1934, and of the Greenwell Medal of the North of England Institute of Mining Engineers in 1950; by the Chairmanship of Section C of the British Association in 1935; and by election as Fellow of the Royal Society in 1936. He also served on the Geological Survey Board (1936–40) and the Fuel Research Board (1943–8). It is good to think that an unassuming and modest person such as George Hickling, who never went out of his way to enhance his reputation, should be so appreciated by his colleagues.

Dr. Hickling was associated with two G.A. field-meetings—those to the Montrose area in 1912, and to Northumberland and Durham in 1931—and contributed both to the 'guides' and to the accounts of these meetings.

He married, in 1910, Gertrude Hermine Geiler, who was to be known in Newcastle as a doctor with a deep interest in child-welfare. The later years of their life together were clouded by ill-health; his wife died in December 1952. A son and two daughters survive. In June 1954, he married Miss Grace Watt, M.A., but was, alas, to live for less than eight weeks longer. The deepest sympathy will be felt for his family and relatives.

T.S.W.

HERBERT HOMESHAW was born in the Midlands in 1902 and died suddenly, when on holiday, in Easter week 1954.

After leaving school he was apprenticed to an engineering works but soon joined a firm of chartered surveyors in Newcastle-upon-Tyne. On qualifying in 1931 he joined the valuation office of the Inland Revenue and served in Newcastle-upon-Tyne, Exeter, London and finally as District Valuer for Bristol.

He was interested in the whole of the countryside, but made a serious study of geology. He was a member of the Bristol Naturalists' Society, and at his death was President of the Geological Section. He joined the Geologists' Association in 1949 and was an active member whilst he lived in

London. Subsequently he took part in some of the long Field Meetings.

His intense energy, keen observational powers and joy in living made him a delightful companion in the field. On these accounts many mourn his comparatively early death. He leaves a widow and two children.

F.S.W.

ARTHUR JOHN MASLEN, who had been a member of the Association for sixty years, died in a London hospital on 5 February 1954. Though he was the author, or part-author, of some eight publications on the morphology of various Carboniferous plants (1898–1930), he was perhaps better known to us for his thirty years of geology teaching at Chelsea Polytechnic, both during the day and in the evening. Over that period, he attracted many into membership of our Association, but he himself was seldom able to attend our meetings because of his teaching responsibilities.

Dr. Maslen was born on 6 July 1871 and in 1893 he entered the Royal College of Science to study botany and geology. There he was a Student Demonstrator in Geology from 1895–7 and in the latter year he was awarded the Marshall Scholarship to undertake palaeobotanical research. His practical interest in evening teaching was evident even in his student days for he was conducting science classes at Greencoat School, Camberwell, and at Regent Street Polytechnic in 1894, and this routine continued until 1900. After a short temporary spell in the latter year, demonstrating botany in the University of Manchester, he became for four years a member of the visiting staffs of no less than five London Polytechnics, lecturing in botany, physiology, hygiene and physiography. During this period he was joint author with G. P. Mudge of 'A class book of botany' (1903). However, in 1904, geology came to be a major occupation for he was given a full-time teaching appointment at Chelsea Polytechnic to develop courses in that subject, at first, and for a short time only, as assistant to J. Allen Howe. This position gave him further opportunity to continue his palaeobotanical research and he worked at the Jodrell Laboratory at Kew between 1903 and 1911, in part on his own studies, and in part in collaboration with D. H. Scott. The results of Maslen's research, which included important contributions to structural knowledge of the Lycopodiales, Cordaitales and Pteridospermae, were published in the *Annals of Botany*, except for an early paper on the structure of *Lepidostrobus* in the *Transactions of the Linnean Society*. He prepared his own drawings for publication and those he made of the Pteridosperm seed *Trigonocarpus parkinsoni* were reproduced in Scott's 'Studies in Fossil Botany' and have been copied into other textbooks.

His teaching at Chelsea helped many students; some of these were engaged in professions far removed from geology; others required a geological knowledge to help their work; and as Maslen had become a

Recognised Teacher of the University of London in 1903, so it followed that he prepared many people for its examinations at all standards including theses for research degrees. Several men now following geological careers owe to Maslen's efforts their early success in scholarship.

He had a gentle and kindly manner; he was conscientious and thorough in everything that he undertook and he expected this of his students. When Maslen retired in 1934, he was able to pass to his successor a Department of Geology which was autonomous; this status he had achieved for it two years previously. A further achievement which gave pleasure both to him and to his former students was the award, which came to him in 1932, of the Doctor of Science degree in the University of London.

He is survived by his widow.

C.J.S.

MAURICE ALBION OCKENDEN died on 2 December 1954, at the age of seventy-nine. Since he was a member of a family long associated with well-drilling, geology, as applied to this work, was deeply rooted in him.

As a young man he became interested in oil-drilling and spent some time in the American oilfields.

He joined the Geologists' Association in 1916 and developed a keen interest in the geology of south-east England in particular—an interest quite separate from his professional activities. For many years he regularly attended both field and indoor meetings. He served on the Council from 1943 to 1946.

In his professional capacity he early appreciated the value to geological science of detailed records of boreholes. In consequence, for many years before the notification to the Geological Survey of wells became compulsory he ensured a steady flow of such records to the Survey, for general use, neatly handwritten.

Maurice Ockenden's activities were wide. He was a Freeman of the City of London and a Liveryman of the Guild of Turners. Furthermore, until a few months before his death he was a member of the Council of the London Chamber of Commerce.

F.H.E.

ROY WOODHOUSE POCOCK died, after a short illness, 22 June 1954, while on holiday in Belgium, aged sixty-seven. He was born in 1887, took an honours degree in geology after studying at Birkbeck College, London, and, in 1912, was accepted as geologist on the staff of the Geological Survey and Museum. He was promoted to the rank of Senior Geologist in 1922 and to that of District Geologist in 1937; he retired in 1948.

During the First World War he saw military service in the Gallipoli

Campaign, where his geological knowledge was applied to problems of water supply. Later he was transferred to the Royal Garrison Artillery and posted to Dover Castle. While there he married Florence Williams, who, with their two daughters Joyce and Helen, survives him.

In the early part of his career on the Geological Survey he worked under George Barrow and later under T. C. Cantrill as District Geologists, with both of whom he made life-long friendships. Much of his early service was in the Welsh Borderland and he participated in the production of the maps and memoirs of the following 1-in. sheets: Aylesbury, Hertford, Wem, Stafford, Shrewsbury, Wolverhampton and Dudley. Also he collaborated in the Welch Borderland Regional Guide, and contributed to the Mineral Resources Memoirs on Tungsten and Manganese, on Barytes and Witherite and on Fluorspar. As District Geologist he was in charge of the South Wales and Bristol district and there joined his field staff in mapping Silurian and Old Red Sandstone rocks round Chepstow.

Always a keen field worker, he carried out private work on the Woolhope inlier which he had started as a student, and discovered the Silurian *Petalocrinus* limestone—a rock largely composed of these crinoids which had not previously been recorded in this country—and published an account of his researches in 1930 (*Quart. Journ. Geol. Soc.*). For many years, too, he carried out research into the Cornstones of the Lower Old Red Sandstone which he held to be composed largely of fish-plates, and also into *Pachytheca*, which he regarded as fish-eyes, whereas other authorities class them generally as algae or primitive plants; these lines of research, however, led him to no conclusive results. One of the most important of his interests was the Lower Carboniferous lavas, which resulted in papers on the basalt of Little Wenlock in 1925 (*Summary of Progress*, *Geol. Surv.*) and on the age of the Midland basalts in 1931 (*Quart. Journ. Geol. Soc.*), and in 1934 he published, conjointly with E. S. Cobbold, a paper on the Cambrian area of Rushton, Shropshire (*Phil. Trans. Roy. Soc.*).

In 1932, as a result of his various researches he obtained the degree of D.SC. in the University of London. Also in this year he received the award of the Lyell Fund of the Geological Society of London. Later he served on the Council of that Society (1937–42) and was elected a vice-president of the Society (1941–2).

Pocock joined the Geologists' Association in 1907 and served as Treasurer between 1950 and 1952. A well-known figure at many field meetings, he himself conducted excursions to the Chiltern Hills (1912), Cuffley and Hertford (1913), St. Albans (1913), Hertingfordbury and Bayford (1914), Shenley (1919), Bridgnorth (1931) and, conjointly, to Hereford (Easter 1939) and Wellington, Salop (1945).

He will be remembered by all who knew him as a congenial companion and colleague and for his urbanity, good humour and imperturbability, both during his official career and after his retirement.

H.G.D.

ERNEST WILLINGTON SKEATS was born at Southampton in 1875, and died at Melbourne, Australia, in January 1953.

He attended the Royal College of Science, London, and in 1899 graduated B.SC. in the University of London, having achieved first-class Associateships of the Royal College in both Chemistry and Geology. His earliest substantial work was on dolomitisation, in which he brought to bear his field experiences in the Tyrol, his examination of samples from the Funafuti boring, from Christmas Island and other localities, and his knowledge of chemistry as well as of geology. This work was essentially geochemical and he always advocated the joint study of geology and chemistry for students wishing to specialise in mineralogy and petrology. He accepted the Chair of Geology and Mineralogy in Melbourne in 1904, succeeding J. W. Gregory who had transferred to Glasgow, and he subsequently devoted himself wholeheartedly to the development of his Department and the University. Petrology remained his major research interest, and he made notable contributions to our knowledge of the Devonian dacite-granodiorite suite in Victoria, the Cambrian basic volcanics, the Middle Devonian diorite and lamprophyre dykes, especially at Woods Point, and the Tertiary lavas, particularly the alkali rocks. He was very interested in mining, and was a member of the council of the Australasian Institution of Mining and Metallurgy for many years and President in 1924–5. He was nominated to Honorary Membership in 1952. In 1921, he was awarded the Clarke Medal of the Royal Society of New South Wales, and the Mueller Medal of the Australian and New Zealand Association for the Advancement of Science in 1937.

His energies and administrative abilities were widely used in committee work, and for many years he was on the Council of the Royal Society of Victoria and the executive committee of the Australian National Research Council. In the University he was President of the Sports Union for a number of years and President of the Professorial Board 1922–4. He was also Patron, and first President, of the Gilbert and Sullivan Society, and generations of students remember his extempore renditions of excerpts in the evenings of 'long excursions'. He became a member of the Geologists' Association in 1899.

Skeats was a man of clear and definite ideas. To his students he was a stern critic, but a man who they could trust. One sensed the deep feeling for his science, his culture, and his fellows that lay behind a sometimes brusque manner. The humanity of his feelings he often showed in acts of kindness during his long lifetime, and in his bequests, in which he remembered many who were his colleagues in professional life, supported those societies with which he had been associated as a geologist, and assisted his old department in the University of Melbourne. His many friends remember him as a leader in his sphere, and will long keep his memory green.

E.S.H.

FREDERICK H. WORSFORD was born at Eastry, near Sandwich, Kent, in 1870 and died on 10 October 1954 at the age of eighty-four years. He became a member of our Association in 1925.

He was a keen amateur geologist and archaeologist, and a skilled photographer who had studied the Canterbury district with zeal and care and collected at several localities. In the Isle of Sheppey he found a number of new fossils in the London Clay which were described in the classic monograph on the London Clay by the late Mrs. Clement Reid.

Of no less importance were his discoveries of mammalian bones in the cliffs between the Swalecliff Brickworks and Priests Corner, where the London Clay is overlain by irregular spreads of loam, brickearth and rubble. His finds included the species *Hippopotamus major*, *Elephas primigenius* and *Hyaena spelaea*. The fine collection which he made was exhibited to members of the Geologists' Association when they visited the Canterbury district in 1925. Afterwards he published a description of them in our PROCEEDINGS (**37**, 326–39). Below the mammaliferous bed, here about five feet thick and some ninety feet long, he collected numerous shells of land and fresh-water mollusca, mainly belonging to three or four species, which are also described in his paper.

Another subject which greatly interested him was the amount and rate of erosion of the north Kent cliffs. The loss of land at Reculvers had been recorded from the early sixteenth century, when the sea shore was about one and a quarter miles from the Church and Roman Camp, until the beginning of the nineteenth century when it was only five yards away, representing a loss of 6600 feet in 250 years or about twenty-six feet per annum. Worsfold had observed that the cliff at Swalecliff has receded about 160 feet in sixteen years, or ten feet per annum. He had been informed that, about 1862, the Nore Light, off Sheppey, could not be seen from Tankerton, but by 1925 the light became clearly visible as a result of the Isle having lost nearly a mile of land!

The archaeology of North Kent also attracted his attention and he kept account of the occurrence of the 'Thames Picks' which are dredged up in considerable numbers by the oyster trawlers from the 'Flats', about one and a half miles from the coast. They are either dark grey, and barely show patination, or are dark brown. The latter constitute about 20% of the finds and are found off the West Last buoy, in the 'Stone Channel' of the fishermen. Some measure one foot by two inches and show the tranchet flake at the end. Long narrow flakes, some nine inches in length, and triangular in section, have also been recovered. Probably they are of Mesolithic Age.

Some of the implements belonging to the Neolithic and Early Bronze Ages appear to have been recovered from brickearth. Mr. Ll. Treacher had collected polished celts in brickearth at Great Marlow, and a bowman's wrist-guard or bracer was dug out near Sturry, some four feet below the surface of the Terrace deposits.

Worsfold's assistance during the official investigations of the gravels at Sturry, near Canterbury, by Mr. Reginald Smith and the writer was of great value, for he gave freely of his knowledge and was always ready to indicate the sites where his own observations had been made. Some of his results have been published in our PROCEEDINGS, but it is to be regretted that partly owing to his hesitancy in drawing conclusions, so much has been lost.

H.D.

# Piedmont profiles in the arid cycle

by W. G. V. BALCHIN and N. PYE

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**ABSTRACT:** The paper discusses the origin of piedmont profiles in the arid cycle of erosion, with particular reference to the Sonora and Mohave Deserts of Arizona and California. The various physiographic elements may be divided into those produced by erosion and those produced by the accumulation of the eroded material. In the former group fall the retreating mountain front, the pediment and the river terrace, whilst the latter includes the bahada, the peripediment (alluvial zone) and the playa. The relative importance of each of these two groups determines the resulting piedmont profile. At least sixteen combinations appear possible but some are more common than others, and the evidence gathered suggests that landscape forms developed under semi-arid to arid conditions are much more responsive to minor changes in lithology and/or climate. It follows that different combinations of the profile elements may co-exist within short distances, and that detailed explanations are only locally applicable. Herein, it is thought, may lie the key to many opposing points of view regarding the origin of certain features; more especially the rock-cut surface or pediment.

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## 1. INTRODUCTION

THE PHYSIOGRAPHIC features of deserts are very varied, but a broad distinction may be made between the great plains and plateaux of the African and Australian areas and the succession of arid, mountain-girt basins of parts of Africa, Asia and North America. It is in the latter area that landscape forms peculiar to the arid cycle have especially developed; more particularly in those localities adjacent to the mountains, i.e. in the piedmont zones. Here the mountains often stand out from the adjacent plains with startling abruptness. From a distance the hill slopes appear remarkably steep, rising precipitously to jagged peaks and forming the *sierra* type of mountain range. Closer inspection reveals that the plain itself rises in a gentle slope to the mountain foot, but there is then an abrupt change in the mountain gradients without any transition zone of intermediate slope, or any region of low foothills. It is evident that the dominant processes responsible for the formation of the mountain slopes must differ considerably from those responsible for the plains. The mountain slopes are sometimes gashed by gullies down which intermittent streams tumble in torrential courses to lower levels. When these streams reach the plain their velocities are checked and transporting powers reduced, with the result that their loads are deposited in fan-shaped accumulations. Each fan results from a single mountain stream and normally this divides radially from the apex of the fan. The load is thus distributed, and in the course of time adjacent fans may join to form a continuous alluvial deposit, or *bahada*, flanking the mountain foot.

Further examination shows that the plain itself may present either an erosional or an alluvial aspect. Bare planed rock surfaces, which have been variously referred to as *pediments*, *rock pediments* or *sub-aerial benches*, may form an important element in the piedmont zone. These may stretch away from the mountain foot, eventually disappearing beneath gently sloping plains of alluvial accumulation sometimes referred to as *graded piedmont slopes*. These in turn may pass into either a dead flat plain or *playa* associated with a basin of interior drainage, or into the dissections of a through-flowing river.

There thus exists a fundamental difference between the smooth graded profiles associated with the humid cycle, and the sectioned profiles, with angular junctions, typical of the arid cycle. Some seventy years have now passed since Gilbert first touched upon these differences, and during this time identical features have been described from a variety of arid areas ranging from Arizona, California, Utah, Colorado and New Mexico in the United States to Chile, Mongolia, Australia and many parts of Africa. It seems clear that these landscape forms in mountain areas are concomitant with arid conditions. Along with many purely descriptive accounts there have also appeared hypothetical works in which theories have been advanced to account for the origin of these features. The planed rock surface has probably given rise to most controversy and rival schools of thought have variously suggested that the origin is to be found in the recession of the mountain front by weathering processes (Lawson, 1915; Bryan, 1936; Davis, 1930); or that the feature results from lateral corrasion by ephemeral streams operating in a zone between degradation in the mountains and aggradation in the plains (Gilbert, 1877; Johnson, 1931; Blackwelder, 1931; Howard, 1942); others have looked to special processes such as sheetflood erosion (McGee, 1897) or sheetwash erosion (Rich, 1935) which are known to operate under arid conditions. The angle between the mountains and the plains, together with the nature of the retreat of the mountain slope, has also given rise to discussion. Deductions can be made from some of the theories that, so far as the present authors could ascertain, had not been fully tested in the field, and it was with this object in view that a small expedition was organised in 1952 to visit the Sonora and Mohave deserts of Arizona and California.

In the Sonoran Desert there are nearly a hundred isolated mountain ranges, varying from five to ten miles in width, and rising from five to six thousand feet above debris-filled basins some twenty-five to thirty miles in extent. The mountains consist of granite, gneiss and other crystalline rocks, in places capped by lava flows, and they have the typical fault-block form common throughout the Basin and Range province. In the piedmont zones we find the canyons, fans, bahadas, pediments, and alluvial zones already mentioned. Whilst interior drainage to enclosed basins or bolsons occurs, it is by no means universal, and in many parts there are through-flowing (although intermittent) rivers such as the Gila, Salt, San Pedro and Santa Cruz. Combined with the fact that much of the area has slopes on which water might run directly to the sea, were there enough rain, it is perhaps more correct to say that this is largely an area of exterior drainage.

For this reason, therefore, attention was also directed to the Mohave Desert of Southern California. This, with somewhat similar topography and climatic conditions, is characterised by interior drainage. Smaller ranges of mountains, more widely dispersed, here demarcate extensive infilled bolsons, the centres of which are marked by soda lakes, borax lakes, and dry lakes. This is a region of rising base levels, whereas much of the Arizonan desert area is now controlled by a falling base level. During the course of the expedition, field observations and slope measurements were made throughout these areas and over several thousand miles of territory.

## 2. THE LONGITUDINAL PROFILE[1]

(a) **The mountain slopes** in the region studied ranged from 25° to almost 90° from the horizontal, and in all cases rose abruptly from the adjacent morphological feature. Whatever the angle, there is a distinct tendency for it to remain almost the same until the crest of the slope is reached. There is also a correlation between the angle of slope and the type of rock; isolated hills, mountain slopes and canyon walls cut in the same rock all tend to assume slopes of the same angle under arid conditions, and it seems quite evident that with unimpeded removal of the weathered debris these slopes retreat parallel to themselves. The actual slope which forms is controlled by the resistance to weathering and by the physical properties of the rock. The nature of any jointing in the rock is very significant, for this is largely the factor deciding the sizes of the blocks which may be detached from the rock face. The resistance of these blocks to disintegration, together with their size and number, materially affects the angle of rest and usually decides the slope for a particular rock. Whilst theoretically any angle becomes a possibility, in actual practice one usually finds either a precipitous clean-faced slope, approaching the vertical, and related to widely-jointed rocks, or boulder-strewn slopes ranging between 25° and 45° which are related to more closely-jointed rocks (Plate 5, A). Certain types of granite, gneiss, some massive lava flows and fine-grained porphyritic rocks give rise to precipitous slopes, and here recession takes place either by prolonged uniform surface disintegration, or by undermining at the base of the more resistant rocks. The presence or absence of talus depends on the relative rates of weathering and removal. The more normal granite (e.g. Sacaton Mountains, Arizona) (Plate 5, B), gneiss (Santa Catalina Mountains, Arizona) and lava (Tucson Mountains, Arizona) weathers into a boulder-strewn slope of 30–50°, interrupted by occasional cliffs related to the more resistant rocks. The spacing of the jointing controls the size of the boulders and these may vary from less than a foot to several feet in diameter: hence normally fine-grained granites and gneisses, with closely-spaced joints, will give rise to gentler mountain slopes than the coarse-grained types. The rate of change on all these slopes must be very slow indeed in the absence of any violent water action. Shreve, for instance, cites cases of *palo verde* (the greenstick tree) up to 400 years old growing between the boulders and so placed that little or no movement can have taken place in the tree's lifetime.

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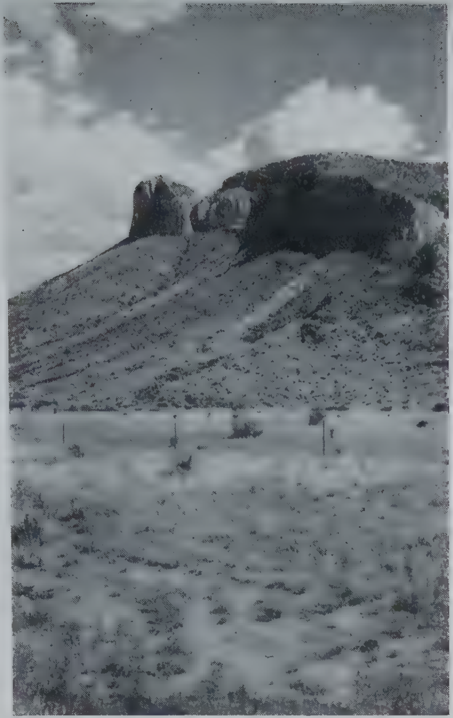
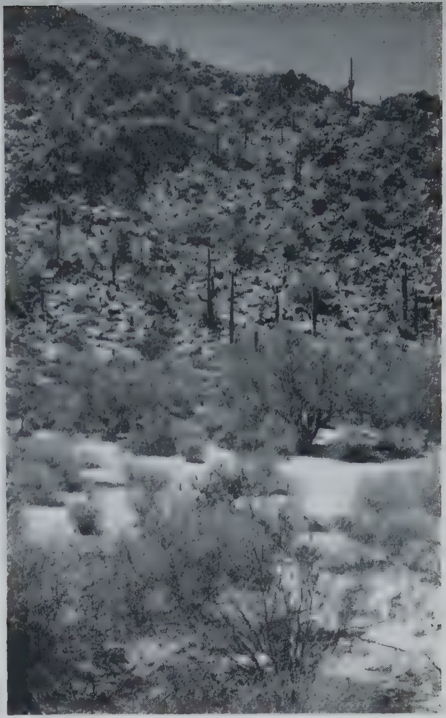
[1] Profiles taken approximately normal to the run of the mountain front.

But disintegration does continue, the bedrock decaying along the joints and the occasional rain washing away the fine fragments. From time to time boulders are set in motion down the slope and perhaps break to pieces *en route*. By these processes the mountain front slowly retreats, while maintaining its angle of slope. Whether talus or material is found at the mountain foot depends on the local balance of forces between the prevailing climatic conditions and the rock resistance.

(b) **The bahada** form arises in the piedmont zone, where the rainfall is sufficient to produce streams rather than rain wash, and it is the counterpart of canyon cutting at higher levels. The gradient of the individual fan is intimately related to the size of the incision at the rear. Short precipitous gullies on the mountain front pass into steeply graded fans in the piedmont zone, slopes of up to 20° being noted. Large canyons which have deeply dissected the mountain area merge into broad fans of very small gradient. In these cases slopes will normally be less than 7° and may be as low as 1°. The alluvial fans of the Santa Catalina Mountains, near Tucson, Arizona, have a radial extent of some four miles and slopes of 5° in the steepest parts, dropping to 2° in the lower parts. It is the larger and less steep fans that coalesce into the bahada to form extensive gently sloping plains which, from a distance, may be confused with the pediment. Although there are superficial similarities to the pediment, a close examination soon reveals the bahada's true nature. It is built up to some thickness with poorly-



A. Peripediment reaching to waste-mantled mountain front with precipitous summit slopes. Sharp angular junctions. Mescal Peak south-west of Tombstone, Arizona



B. Granitic boulder-strewn slopes giving place abruptly to pediment with thin veneer of fine-grained sediment. Sacaton Mountains, Arizona

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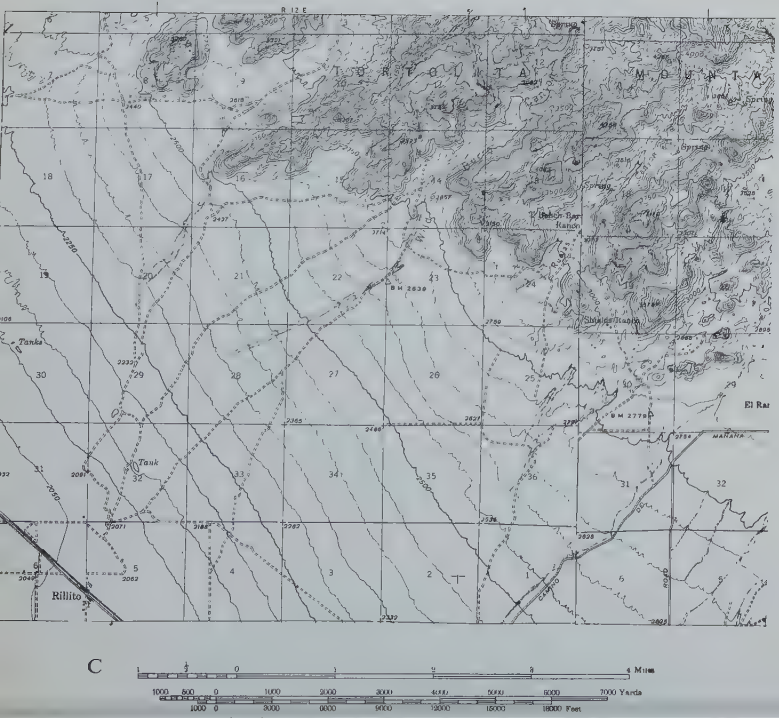
R 12 E
TORTOLITA MOUNTAINS
Spring
Bench Bar Ranch
Shields Ranch
BM 2630
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18000 Feet

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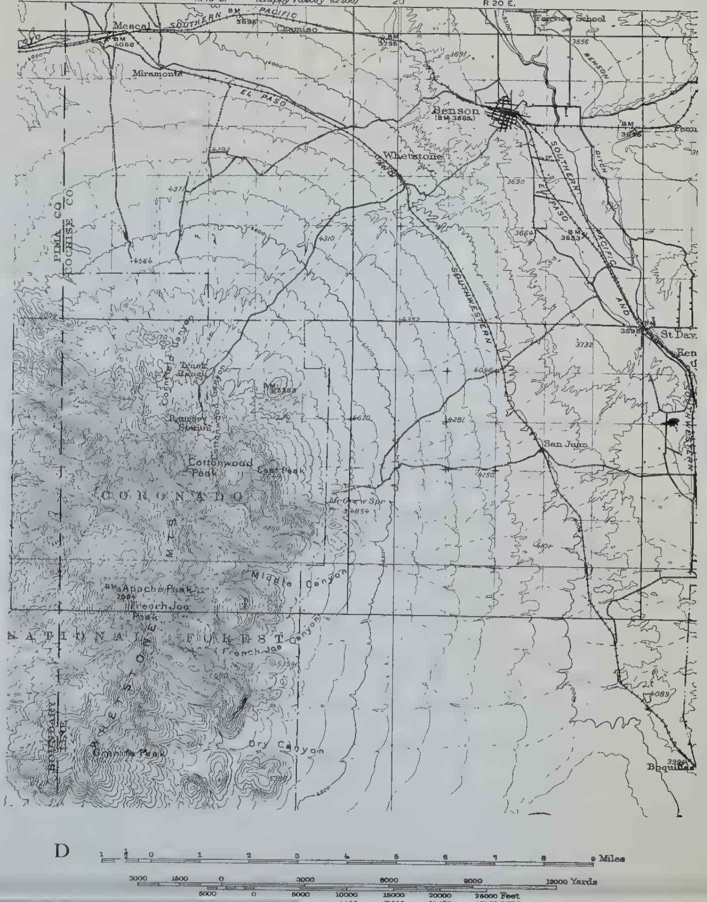
R 20 E.
SOUTHERN PACIFIC
EL PASO AND SOUTHWESTERN
Mescal
Chamiso
Miramonte
Benson (BM 3585)
Whetstone
Farmer School
BENSON DITCH
St. David
San Juan
Boquillas
PIMA CO
COCHISE CO
Trunk Ranch
Rangers Station
Cottonwood Peak
East Peak
McGrew Spr
CORONADO NATIONAL FOREST
WHETSTONE MTS
Middle Canyon
Apache Peak
French Joe Peak
French Joe Canyon
Dry Canyon
Granite Peak
BOUNDARY LINE
9 Miles
12000 Yards
25000 Feet

D

stratified detritus and large included boulders deposited under torrential conditions; sections reveal that near the surface each layer is almost parallel to the particular fan surface. The composition is such that many are, in fact, rock debris fans rather than 'alluvial' fans in the conventional sense of the word (Plate 6, A). The longitudinal profile is definitely a shallow concave curve, with the concavity upwards, and the gradient increasing steadily towards the mountain front. The feature masks the mountain front and forms a zone of aggradation along its foot. The base of the bahada is normally revealed by a clear junction angle with the next morphological element in the sequence except in those cases where gradients of 1°, or less, obtain.

(c) **The pediment,** at upper levels, has probably been confused by many with the mature low gradient bahada, and at lower levels with the alluvial zone (Fig. 1), but the pediment proper is very different from either because it consists of a gently inclined planed rock surface which rises to the foot of the mountain front and cuts indifferently across rocks of varying lithology and structure (Plate 6, B; Plate 5, C, D). The gradients all fall within the range $\frac{1}{2}$°–7°. Whilst the differences in slope are slight, they often appear to be correlative with other factors. Slopes opposite to large canyons are commonly more gentle than those opposite to small canyons, whilst the pediment which runs to the foot of the mountain front has usually a slightly higher gradient than the areas opposite to the canyons.[1] It was also noted that rocks weathering into a coarse debris (e.g. Baboquivari Mountains) give rise to slightly steeper pediment slopes than those which break up into a fine debris (e.g. the Sacaton Mountains); whilst rocks such as andesite lava (e.g. near Ajo), which weather to large resistant blocks, fail to yield any pediment forms at all. Differences in slope rarely exceeded one or two degrees, and were often imperceptible to the eye, but the trend does throw some light on the origin of the pediment. It is clear that stream size and lithological factors must not be overlooked.

Confusion with the other landscape forms has undoubtedly arisen because, in places, the pediment is often overspread with a thin veneer of gravelly detritus which may conceal much, if not all, of the rock surface. A further difficulty arises in that the pediment disappears beneath the next feature—the graded alluvial zone, in most cases—and rarely seems to attain any great width. The longitudinal profile of the visible section is frequently of a uniform gradient and thus contributes little towards a solution of its origin. For if it is a water-eroded feature, i.e. related to either lateral corrasion (Johnson, 1931, 1932a; Gilbert, 1877; Blackwelder, 1931a; Howard, 1942), sheet-flooding (McGee, 1897) or sheetwash (Rich, 1935), its profile should show a concave tendency; whilst if it is due to the normal recession of the mountain front with a rising base level (Lawson, 1915; Bryan, 1925) its profile should show a convex tendency.

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[1] Contrary to the theoretical deduction of J. L. Rich (1935).

In the present investigation various attempts were made to trace with an auger the sub-alluvial rock floor of buried pediments in the Sierrita and Tortolita Mountains, near Tucson, but the gravelly nature of the detritus made it impossible to determine the depth of the rock surface with any degree of accuracy. Experience showed that this method could only be used in the very fine deposits well away from the mountain front, but here the depth of the detritus was considerably beyond the range of the normal auger. Well and ground water-borings are however sometimes of great value in giving an indication of the depth of the detritus, although they rarely reveal the actual rock floor as the borings are normally stopped as soon as water is reached. Now, however, a great deal of evidence has been collected by the Ground Water Division of the United States Geological Survey and in many areas this definitely points to an increased rate of accumulation outwards from the mountain front, and suggests that the sub-alluvial rock floor is probably convex upwards, as Lawson supposed (1915). This particular aspect of the problem could probably be resolved by sample seismic surveys which may well be made before very long in view of the growing economic significance of ground water supplies, coupled with the problem of falling water table levels in these areas.[1]

If the term pediment be confined to the exposed and visible portion of the rock surface, then the areal extent and incidence of the feature is probably very much less in both the Sonoran and Mohave areas than previous writers have estimated. McGee thought that some two-fifths of the Sonora Desert region consisted of pediment plains but the 1952 traverses did not reveal any very extensive exposure of bare piedmont erosion surfaces, and those that were noted, more especially in the Tortolita, Baboquivari and Sierrita Mountains, together with the Ajo region, presented a very hummocky surface and were by no means as smooth as might have been expected from the literature. These pediments were runnelled and were clearly being influenced by stream-flood action. Dissections of up to fifteen to twenty feet in depth were by no means uncommon, although from a distance smooth skyline profiles were often simulated. A regular smooth planated rock surface may be a rarity, in fact, but a smooth surface profile often occurs at lower levels when the rock has a cover of alluvial deposits. What is not yet clear is the permissible depth of the veneer that a rock plain may have and still remain a true pediment, rather than becoming a true sub-alluvial rock bench. One criterion which might eventually prove useful is the depth of scour of the intermittent stream action (Howard, 1942; Tator, 1952a).

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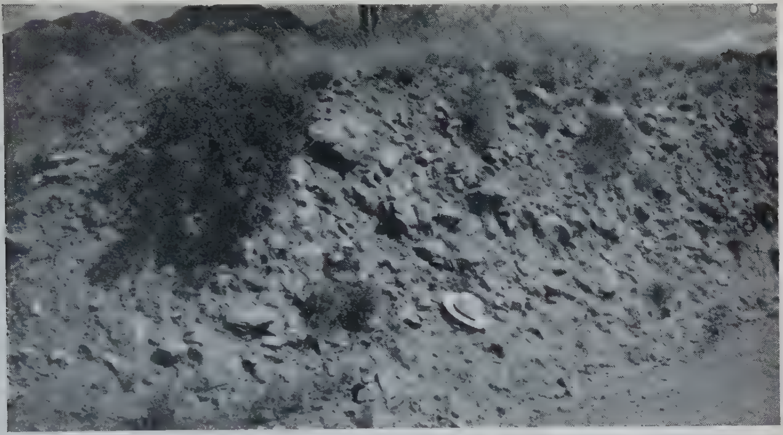
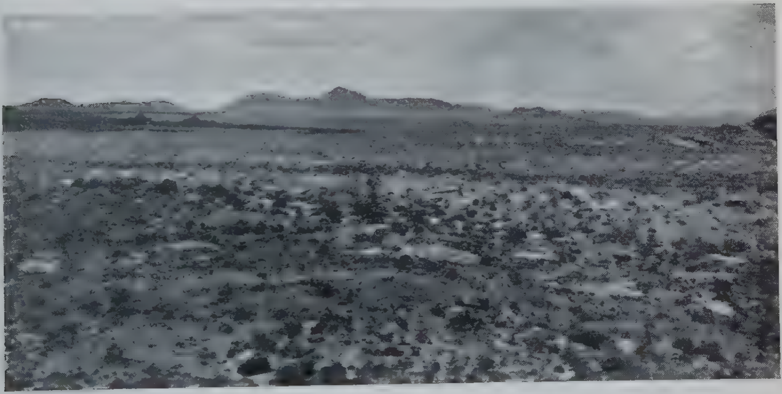
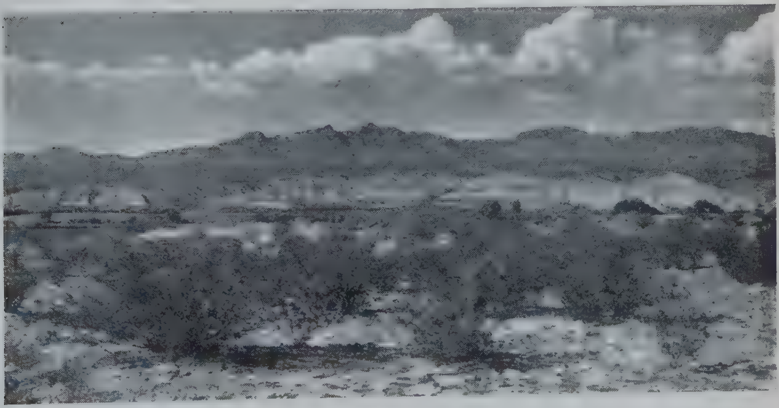
[1] See W. G. V. Balchin & N. Pye, 1953. The Drought in the South-Western United States. *Weather*, Royal Meteorological Society, London, 8, 223–6.,



A. Section through bahada zone, Santa Rita Mountains, south of Tucson, Arizona



B. Rock pediment of the Sierrita Mountains south-west of Tucson, Arizona



C. Rejuvenated peripediment in the Gila River valley near Safford, Arizona

(d) **The alluvial zone** succeeds the true pediment as the next element in the sectioned profile. The surface slope of the first part is normally less than five degrees, and may fall as low as fifteen minutes of arc (e.g. south of Tucson on the flanks of the Sierrita Mountains). The skyline longitudinal profile does not reveal the junction, which is a zone rather than a line, and this can only be found by traversing the ground. Many previous writers have described pediments with alluvial covers up to several hundred feet in thickness, although most talk in terms of a 'thin veneer' without specifying the actual depth. We feel that a distinction should be made between the rock surface which has a really thin veneer but is still within the range of sub-aerial weathering agencies, and hence still subject to change, and the rock surface which is buried beneath a thicker alluvial cover and hence protected from further change. It would seem logical to restrict the use of the term pediment to the former case and to use the phrase sub-alluvial bench for the latter.

That part of the alluvial zone above the 'bench' which continues the slope of, and grades into, the pediment is of constructional rather than degradational origin, and should be distinguished from the pediment. As it is peripheral to the pediment, and often superficially similar, Howard's term *peripediment* (1942) might usefully be confined in future to this feature, and in fact seems to be so used in Child's work (1948) on the Little Colorado Region. The combined pediment and peripediment may then be described as a *pediplane* (Howard, 1942). With this distinction the depth of the detritus on the pediment would be restricted to the depth of scour of any intermittent stream action. This would normally be measured in inches, although exceptionally it might be measurable in feet (Fig. 1).

Usually the upper parts of the peripediments in the Sonora and Mohave

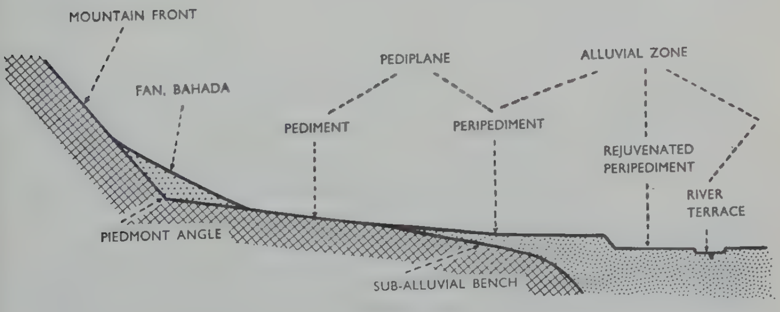


Fig. 1. Elements in the Piedmont Profile

Deserts are composed of detritus which is poorly sorted and which frequently resembles deposits of a torrential character. But this is probably due to the occasional sheetflood and streamflood which sweeps down and across the pediment, carrying all before it, until with decreasing speed first the coarse and then the fine load is dropped. Downslope on the peripediment, however, the material is better sorted, becomes much smaller in size, and eventually passes into a fine deposit, especially in the granite areas (e.g. The Sacaton Mountains). The surface often shows the effect of an occasional sheetwash but the shallow shifting channels caused by stream flooding are clearly in evidence, and it is along these that the vegetation will often be found to be growing. Normally the thickness of the alluvial deposits seems to increase downslope and well-borings, together with occasional dissections, reveal depths of up to 200 ft. Beyond this amount there may be a sudden increase to several hundred, and sometimes more than a thousand, feet of sediment, marking the infilling of a fault-trough or basin (e.g. the Tucson bolson). Conditions such as these indicate a past history of rising base levels, and are well illustrated in the Mohave Desert (e.g. between Amboy and Barstow). The peripediment may be terminated by another similar feature descending from an opposite piedmont slope, or by a through-flowing river, or by a playa. In all cases the line of demarcation is clear and distinct. Even with the playa, although the slope may change from something less than one degree to zero, the change is clearly shown by the sudden cessation of the scanty vegetation. The gleaming white perfectly flat playas of the Mohave desert (e.g. Rogers Dry Lake, Soda Lake, etc.) carry salt, soda and borax deposits, which, together with the intermittent inundations, effectively eliminate most, if not all, types of vegetation. Morphologically these are areas of rising base-levels.

Elsewhere, however, intermittent streams or through-flowing rivers may terminate the peripediment. The intermittent streams can co-exist with a rising base-level but the through-flowing continuous river may give either a relatively stable base-level, or may show rejuvenations with a consequential dissection of deposits which have accumulated under different conditions. The latter is commonly found in southern Arizona where successive rejuvenations of the rivers have dissected the peripediment, and also in places the pediment. Along the Santa Cruz, San Pedro and Gila Rivers up to four marked stages, cut in loose or poorly-consolidated material, can be distinguished, and these rise from the present floodplain in a series of clear-cut steps. But whilst the lowest step is a flat floored floodplain terminated by a river-cut cliff, the higher stages have slopes similar to the peripediment, and are terminated by bluffs apparently retreating parallel to themselves. These appear to be rather special forms, initiated by river action, but developed further under the prevailing semi-arid conditions. They may be regarded as rejuvenated peripediments and would merit a more detailed study and survey than time permitted in the present investigation (Plate 6, C).[1]

All the possible elements in the longitudinal profile have now been described but the actual profile which results in any locality will depend on the particular combination of the elements prevailing in that area. The boulder-strewn mountain front may give place to the rock pediment and then pass into the alluvial zone (Fig. 2, A) as in the Sierrita Mountains. In other localities (e.g. the Sacaton Mountains) the alluvial zone extends to the base of the mountain front and completely masks the pediment (Fig. 2, B), or the presumed pediment, in the absence of information from well-borings. Elsewhere the mountain front may be mantled by a well-developed bahada which gives place to the pediment, and then the peripediment (Fig. 2, C), but this condition did not seem characteristic of the areas visited in 1952. The situation shown in Fig. 2, D, where the bahada passes directly into the alluvial zone without exposure of the pediment (e.g. the Santa Rita Mountains in Arizona and near Amboy in the Mohave Desert) was much more prevalent.

We have already seen that the peripediment may be terminated in the lower parts in four different ways. With a rising base-level either two adjacent peripediments will make a simple junction or the central area will be occupied by a playa or dry lake. With a falling base-level the junction will either be occupied by a simple or a rejuvenated river system. Since any of the four possibilities sketched in the preceding paragraph may be combined with any of the four peripediment terminations there are, theoretically, at least sixteen different profiles possible, any one of which may arise depending on the balance of past and present morphological processes at work in a particular locality.

## 3. THE TRANSVERSE PROFILE[2]

An examination of the transverse profile of each of the morphological elements distinguished so far reveals certain characteristics which contribute to an understanding of their formation. The simple mountain front normally presents a uniform or 'level' profile, apart from those parts which have been gullied or canyoned. The bahada has an undulatory transverse profile, since it is made up of a series of coalescing fans. With steeply graded fans these undulations will be very conspicuous, but in the mature low gradient bahada they may well be imperceptible.

When the pediment is considered, however, we find that the theorists

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[1] Similar features have been described and mapped in the San Acacia area of New Mexico by C. S. Denny (1941), four 'pediment terraces' being distinguished, and in the Upper Rio Puerco Valley of New Mexico by Kirk Bryan & F. T. McCann (1936), where two 'pediments' and two river terraces are described.

[2] A direction approximately parallel to the run of the mountain front.

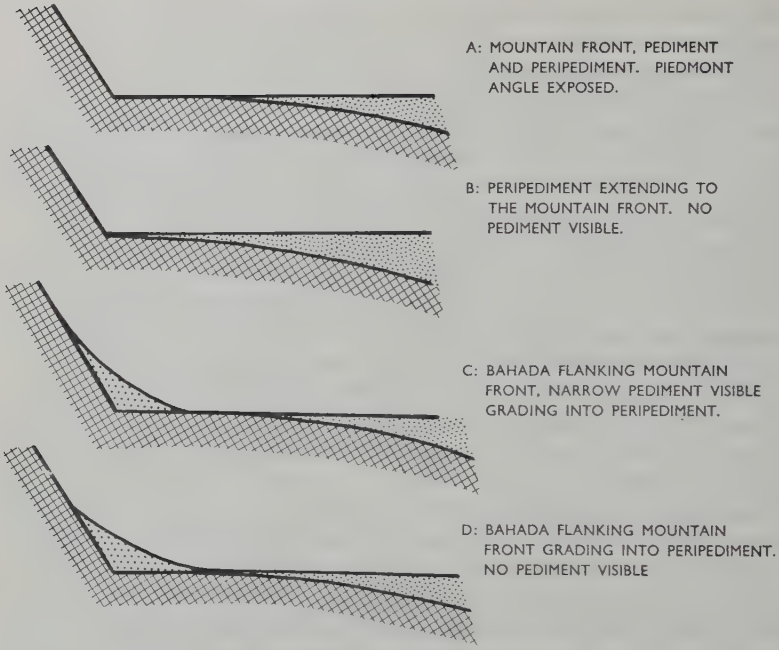
A: MOUNTAIN FRONT, PEDIMENT AND PERIPEDIMENT. PIEDMONT ANGLE EXPOSED.
B: PERIPEDIMENT EXTENDING TO THE MOUNTAIN FRONT. NO PEDIMENT VISIBLE.
C: BAHADA FLANKING MOUNTAIN FRONT, NARROW PEDIMENT VISIBLE GRADING INTO PERIPEDIMENT.
D: BAHADA FLANKING MOUNTAIN FRONT GRADING INTO PERIPEDIMENT. NO PEDIMENT VISIBLE

Fig. 2. Profiles in the Piedmont Zone

postulate the existence of three possible conditions: essentially level; upwardly convex or upwardly concave transverse profiles. Sheetwash and sheetflood action would, it is held, produce a level transverse profile; lateral planation by streams radiating out from canyons cut in the mountain front are said by Johnson (1932a) and Howard (1942) to be capable of producing rock fans with an upwardly convex transverse profile. If, however, the emphasis is placed upon stream-flood erosion (Davis, 1938), then the profile becomes undulatory and upwardly concave in the neighbourhood of the streams, since any form of integrated drainage will require a general concavity. Examination of the transverse profiles should therefore provide some indication of the mode of origin of the pediment. Apart from the special case of the Gibson Arroyo fan already noted by Gilluly (1937), no clear case of a rock fan was discovered in the areas visited in 1952, and Johnson's claim that the Sierrita Mountains had examples could not be substantiated. Both Field (1935) and Blackwelder (1931a) have also looked for, but failed to find, in the Colorado region the theoretical rock fans deduced by Johnson. In southern Arizona the transverse profile of the pediment is often almost level, except in the dissected areas or opposite to major canyons in the mountain front, and it then becomes trough-shaped, e.g. near Ajo (Gilluly). In the Mohave Desert level transverse profiles seem to prevail.

Across the peripediment, and of course on the playa, level transverse profiles are also found, except for minor undulations in the peripediment related to stream-flood courses. Where a through-flowing river such as the Santa Cruz or San Pedro, has lowered the base-level, however, both the peripediment and the pediment may be heavily dissected. Headward erosion along the minor gullies which develop on the sides of the major drainage lines may cut up the peripediment into a maze of small hills. A great deal of the plain lands of southern Arizona are now characterised by this type of bad land topography, and it greatly increases the difficulty of their utilisation (Plate 6, C).

In addition to the dissection which is clearly related to the lowering of the base-level by a through-flowing stream, there are also cases of dissection of the upper peripediment and the pediment where a rising base-level exists, e.g. the Altar Valley south-west of Tucson. Although water rarely occupies these trenches, the dissection would seem to imply a trend towards heavier rainfall, producing streamflood action rather than sheetwash and rill action.

## 4. THE PIEDMONT ANGLE

One important characteristic of semi-arid to arid topography is the abruptness with which the mountains stand out from the plains. This rarely occurs in the humid cycle of erosion and this particular aspect of the morphology is clearly characteristic of the arid cycle. The junction is especially marked in the absence of the bahada zone (which in places may have buried the true angle; Fig. 2, C & D) and it has been variously referred to as a 'knickpoint' (Field, 1935) or 'knick' (Bryan, 1925; Johnson, 1931, 1932a). Its very common occurrence, however, suggests that 'piedmont angle' might be a more suitable term. The angle results from the juxtaposition of the slope of the mountain front, and that of the pediment or peripediment, and is marked by a dramatic change in the character of the material which rests upon the bedrock of the two components. The gravity-controlled slope of the mountain front, strewn with large and heavy boulders, gives place suddenly to the much smaller material of the pediment, or to fine-grained sediment of the peripediment. Here the slope is controlled by water action, the gradient being the minimum slope on which the supplied debris can be transported (Lawson, 1915; Davis, 1930). The presence of a sharp piedmont angle implies that the weathered material from the mountain front is being removed from its foot as fast as it is produced, and, further, that this removal must take place largely by sheet or rill action rather than by stream action. These considerations apply particularly to the outward-facing mountain front, and exclude the possibility of the angle being produced by lateral corrasion of streams, as in Johnson's rock fan concept. No evidence in support of Johnson's approach was discovered in the field, but sharp angles may be produced in the initial stages of a mountain embayment by lateral stream action. This has also been noted by Howard (1942) in the Sacaton Mountains.

The piedmont angle is most conspicuous and the process most effective when rocks with widely-spaced joints weather without intermediate gradings into large boulders and fine-grained debris: the granite and granite-gneiss of the Sacaton Mountains produce perhaps the best examples (Plate 5, B). The angle is less dramatic, and may in fact be replaced by a concave curve, where weathering into a variety of sizes takes place, e.g. the volcanic Tucson Mountains. The angle of dip in stratified rocks is also a controlling factor, horizontally-bedded rocks clearly favouring a sharp angle whereas strata dipping against the pediment may tend to form a concave profile (e.g. west of Tombstone).

The piedmont angle not only occurs at the mountain foot but is also characteristic of the residual masses which sometimes rise above the pediment or peripediment-like nunataks above an ice cap. These are undoubtedly the remains of ridges which have formed from mountain embayments and have then been further attacked from the sides. These must inevitably grow smaller in size until they are eventually consumed by retreating slopes. The angle between the mountain slope and the plain slope is once again attributable to the two different controlling agencies—gravity on the steeper slopes, and water on the gentler slopes.

## 5. THE PEDIMENT PROBLEM

It seems from the evidence gathered that similar rocks occurring under similar conditions, and acted upon by similar climatic conditions, will produce the same combination of forms, but slightly different rocks under similar climatic conditions, or similar rocks under slightly different climatic conditions, will give rise to a variety of combinations. Herein may lie the key to the reconciliation of many opposing points of view about the origin of the rock-cut surface or pediment.

This feature appears to be the natural result of the parallel retreat of steep slopes (mainly mountain slopes, but minor slopes are also possible) which occur under arid conditions with the unimpeded removal of weathered material. The pediment is a zone across which the weathered material from the 'front' is transported, and the gradient is the minimum slope on which the material can be moved by the available forces. The slope must inevitably rise towards the mountain front as the front retreats, in order that the removal of debris may continue. The removal is effected very largely by sheetflood, sheetwash, streamflood and rill action, and apart from streamfloods these processes appear to have but a limited erosive effect on the rock surface. For its proper development, therefore, the pediment requires a finely-adjusted balance between the rate of weathering on the mountain front and the rate of removal of the debris: this will be determined by the interplay of the lithological and climatological factors. 'Process' in the cycle of events may also to some extent be dependent on the 'age' reached.

Excessive weathering leads to an accumulation at the mountain foot temporarily burying the piedmont angle and the pediment, whilst excessive rainfall accelerates canyon cutting and produces bahadas, partly burying and partly dissecting by streamfloods the pediment and peripediment. The latter conditions seem to have influenced a great deal of southern Arizona of recent geological date.

The alluvial zone sometimes extends to the piedmont angle and the pediment disappears from view. This is more likely to occur in the early stages of the cycle when there is a greater surface area of mountain front contributing its weathered detritus to a restricted area of aggradation. Under these conditions Lawson's upwardly convex profile (1915) should arise (probably by a series of minute steps). But with maturity a diminishing mountain front contributes a decreasing load to an increasing surface area so that the pediment emerges and grows in size, although at the same time it may exhibit signs of slow burial by a rising alluvial zone. Theoretically the gradient at this stage could be quite uniform but will probably trend to a shallow upwardly concave curve. In the ultimate stage the mountain disappears completely as two retreating, but opposite fronts, coalesce, leaving behind a slightly convex shaped eminence with an occasional nubbin—well illustrated by the Cima Dome in the Mohave Desert.

Although some measure of unanimity regarding the basic principles of semi-arid landscape formation may now be in sight, many aspects of the problem remain open. Large areas in which this type of landscape occurs still remain topographically unmapped—the remarks and opinions of the early writers are in fact largely based on visual impressions, and these can be very misleading on occasions. But topographic maps, although helpful, do not provide all the desired data. Information regarding the size, distribution and areal extent of the various morphological elements can only be obtained by *morphological* mapping, and at present such maps exist for but very limited areas near Ajo in Arizona (Gilluly, 1937), in the Little Colorado region, Arizona (Childs, 1948) and the Moreno Valley of New Mexico (Ray & Smith, 1941).

Accurate information is also lacking on the depth and exact nature of the sub-alluvial bench: here seismic surveys are probably necessary to provide the required data. There is also more need for quantitative observations regarding those semi-arid processes which do not operate under humid conditions. Here, controlled field observations over a period of time, and perhaps laboratory experiments, might yield additional data on the nature and effect of sheetflood, sheetwash and rill action in relation to lithological differences in grain size.

## ACKNOWLEDGMENTS

The above paper arises from an expedition undertaken by the authors into the Sonora and Mohave Deserts of Arizona and California in 1952. Financial assistance was received from the Universities of London and Manchester, the Royal Society and the Royal Geographical Society, and also the Fulbright Authorities. This assistance is gratefully acknowledged.

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# The zonal stratigraphy of the Blue Lias around Keynsham, Somerset

by D. T. DONOVAN

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**ABSTRACT:** A number of sections through the Blue Lias of north Somerset are described, the majority for the first time, with a detailed record of the exact stratigraphical levels of the ammonites collected. A general account of the lithology of the formation follows, and condensation of the sequence is shown to have occurred at two levels, the more important being in the lower part of the *bucklandi* zone. Sections in the southern part of the area studied show conditions transitional to those found in the Radstock area. Comparison is made between the Somerset sequence and those of the Dorset and Glamorgan coasts respectively. The detailed sequence of faunas is shown to be in many respects similar in all three areas, although the beds in north Somerset are thinner than those in either Dorset or Glamorgan. The succession of ammonite faunas is summarised in a table.

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## 1. INTRODUCTION AND ACKNOWLEDGMENTS

EXPOSURES OF THE BLUE LIAS around Keynsham have deteriorated since the late J. W. Tutcher and his collaborators published their accounts of various local sections. A recent re-examination revealed, however, that the B.R. Saltford Cutting section, previously known only from T. Wright's unsatisfactory accounts (1860, pp. 399–401; 1878, pp. 36–8), still exhibits a continuous sequence through the formation, with the exception of the basal part. A detailed study of this section has been made, and all the other available exposures have been visited.

The principal sections described lie in the adjoining parishes of Keynsham and Saltford, in the Avon Valley between Bristol and Bath. Previously unpublished sections, lying to the south and west, are also included, to demonstrate lateral variation in these directions. Directly south of Keynsham, the Lias of the Radstock area has been exhaustively treated by Tutcher & Trueman (1925), and a number of publications describe the Blue Lias of the area covered by the City of Bristol (Kellaway, 1931, 1937; Stoddart, 1868; Tutcher, 1908).

The writer's primary purpose was to establish the stratigraphical ranges of the ammonites, the palaeontology of which has been described recently (Donovan, 1952). The non-ammonite fauna of the Blue Lias is very extensive, but few of the species are of stratigraphic importance, so a list is included. Faunal lists for some Bristol exposures are given by Kellaway (1931), and for the Radstock area by Tutcher & Trueman (1925).

The writer is indebted to Mr. T. R. Fry for accompanying him in the field and placing at his disposal not only intimate knowledge of the sections here discussed, but also his own notes on exposures now invisible.

## 2. PREVIOUS WORK

The first contribution to the zonal study of the Blue Lias of Keynsham was by Vaughan & Tutcher (1903), who referred briefly (pp. 7, 8) to previous work by Charles Moore, and by the Geological Survey, which had included no attempt to record either the exact stratigraphical position of the fossils or to establish zones. Vaughan & Tutcher studied twelve exposures within the area covered by the present paper, and published composite sections. A fairly detailed account of the lithology was given, but the zonal subdivision was on a very broad basis and it is clear from their palaeontological notes that only limited progress had been made with the study of the ammonites; moreover several genera, including *Waehneroceras* and *Alsatites*, had not been found in the district at this period. Tutcher's other principal paper on the area (1923) marks a great advance in knowledge of its stratigraphy, almost all the known horizons being then recognised. He described exposures opened during the construction of Messrs. Fry's factory at Somerdale, Keynsham, and in order to give an upward continuation of these sections he added an account of Keeling's Quarry at Keynsham, so that the whole succession of the Blue Lias was covered thereby. In the matter of fossil identifications, Tutcher was advised by S. S. Buckman, who adopted his faunal succession for the Hettangian and Lower Sinemurian (Tutcher *in* Buckman, 1918, pp. 278–81).

## 3. DESCRIPTION OF THE PRINCIPAL EXPOSURES

The most important sections will be described here, followed by brief notes on other localities in the next section of the paper. The National Grid Reference of each exposure is placed in parentheses following its name. All the places described fall within the areas covered by Sheet Nos. 156 and 166 of the Ordnance Survey One-Inch Map, 'New Popular Edition'. The locations of the sections described are shown in Fig. 1.

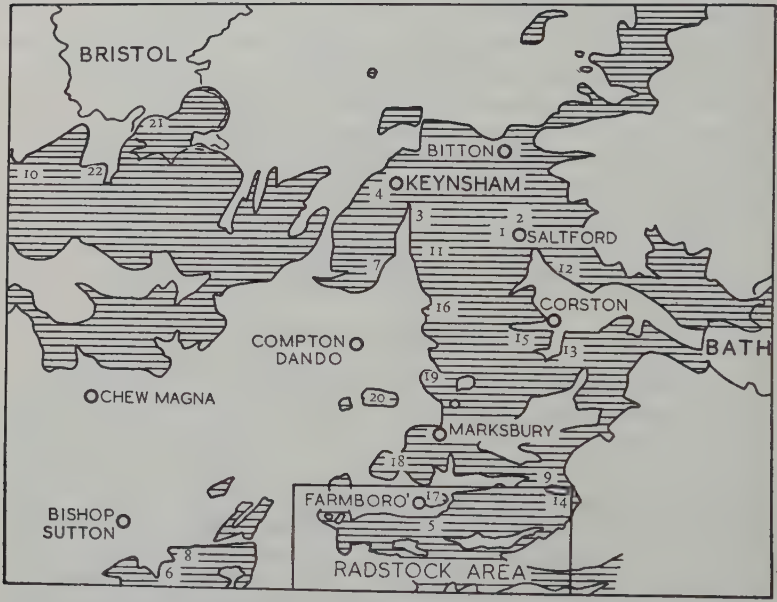

Fig. 1. Sketch-map showing positions of the numbered localities described in this paper. The outcrop of the Lower Lias is shaded. The rectangle at the lower edge of the map marks the boundary of the northern part of the area described by Tutcher & Trueman (1925). Scale three miles to one inch.

In the diagrammatic representations of sections, unornamented beds represent limestone; horizontal shading indicates shale or clay. Consistent differentiation between clay and shale has not been possible since at old exposures these rocks weather back, and cannot be examined in their fresh state. The numbers used in referring to the different beds of a section are arbitrary numbers, allotted in the field, and there is no attempt to make the numbering correspond between different exposures. The vertical scale of the diagrams is five feet to one inch.

**Locality 1:**[1] **Saltford Cutting** (685671 to 681676). Lower Liassic rocks are exposed in the railway cutting north-west of Saltford Station, the best exposures extending for some distance either side of a short tunnel the mouth of which is 670 yds. from the station. The beds dip gently to the west or north-west, so that the lower part of the succession is exposed to the south-east of the tunnel, and the upper part to the north-west, there being some overlap between the two sections. The lowest beds exposed, belonging to the *johnstoni* and *laqueus* subzones, are best seen on the north-east side of the cutting for about 200 yds. from the south-eastern end of the tunnel. The *angulata* subzone is not very extensively exposed, but a complete section, in a nearly vertical face, is preserved on the south-western side of the cutting at a point 70 yds. south-east of the tunnel mouth. Near the top of the bank, both here and on the opposite side of the cutting, is

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[1] See Fig. 1 for this and subsequent numbered localities.

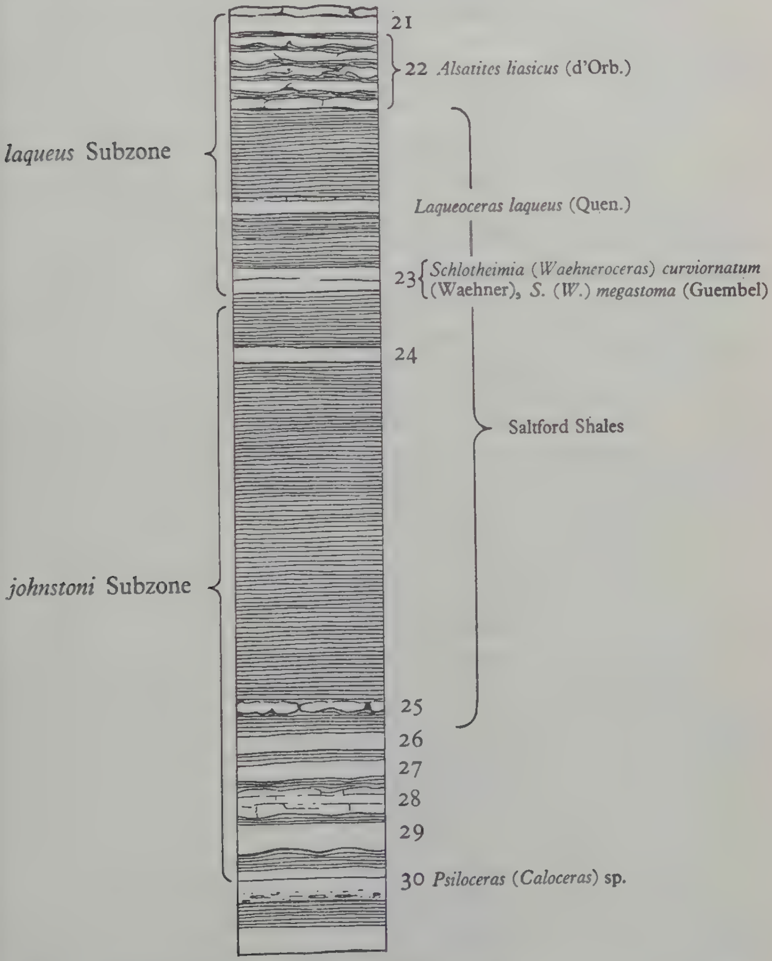
*laqueus* Subzone
*johnstoni* Subzone
21
22 *Alsatites liasicus* (d'Orb.)
*Laqueoceras laqueus* (Quen.)
23 *Schlotheimia* (*Waehneroceras*) *curviornatum* (Waehner), *S.* (*W.*) *megastoma* (Guembel)
24
Saltford Shales
25
26
27
28
29
30 *Psiloceras* (*Caloceras*) sp.

Fig. 2. Lower part of the section at Saltford Cutting. Vertical scale: 1 in. to 5 ft.

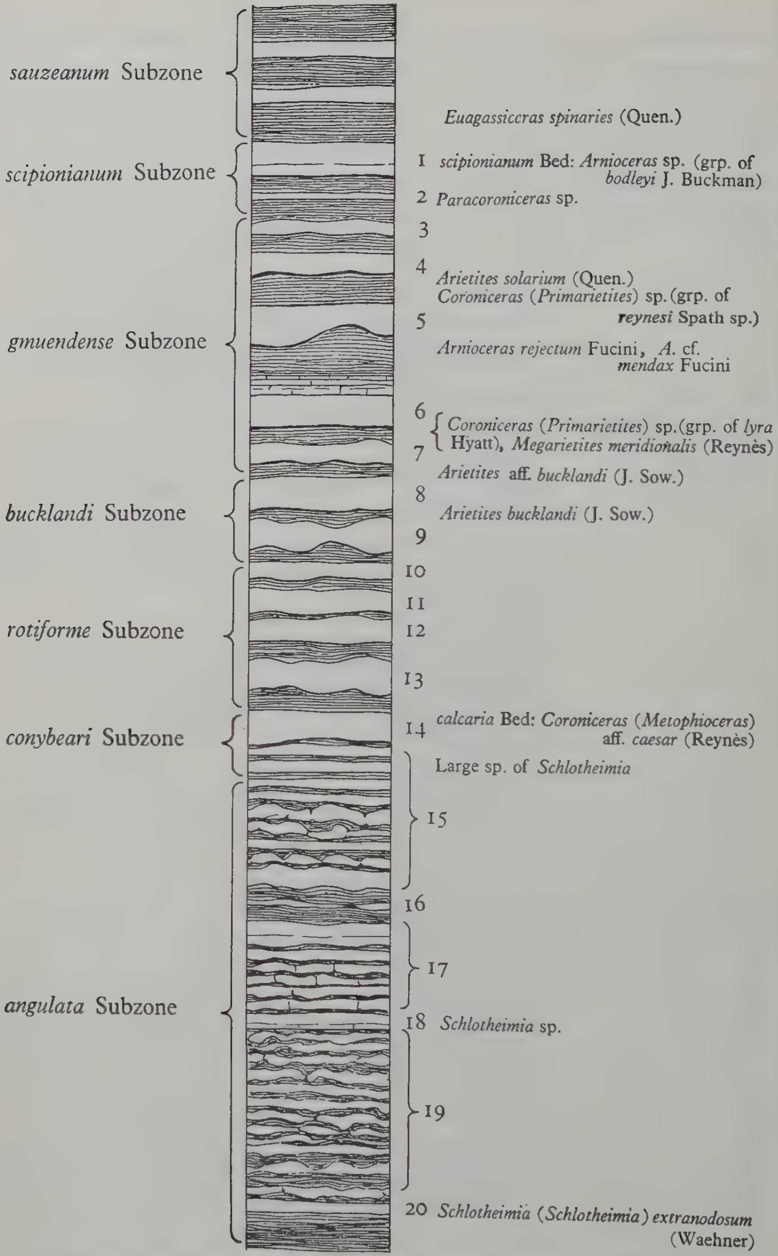
sauzeanum Subzone
Euagassiceras spinaries (Quen.)
scipionianum Subzone
1 scipionianum Bed: Arnioceras sp. (grp. of bodleyi J. Buckman)
2 Paracoroniceras sp.
3
4 Arietites solarium (Quen.)
Coroniceras (Primarietites) sp. (grp. of reynesi Spath sp.)
gmuendense Subzone
5
Arnioceras rejectum Fucini, A. cf. mendax Fucini
6
Coroniceras (Primarietites) sp. (grp. of lyra Hyatt), Megarietites meridionalis (Reynès)
7
Arietites aff. bucklandi (J. Sow.)
8
bucklandi Subzone
Arietites bucklandi (J. Sow.)
9
10
11
rotiforme Subzone
12
13
conybeari Subzone
14 calcaria Bed: Coroniceras (Metophioceras) aff. caesar (Reynès)
Large sp. of Schlotheimia
15
16
17
angulata Subzone
18 Schlotheimia sp.
19
20 Schlotheimia (Schlotheimia) extranodosum (Waehner)

Fig. 3. Upper part of the section at Saltford Cutting. Vertical scale: 1 in. to 5 ft.

exposed the *calcaria* Bed, which is a marker-horizon for linking up the sections south-east and north-west of the tunnel. The remainder of the succession is only exposed north-west of the tunnel. At a point 33 yds. west of the north-western end of the tunnel the base of the *calcaria* Bed is approximately 23 ft. above the level of the track, but the beds below it are not well exposed. The best section in the beds above the *calcaria* Bed is behind a hut on the north-eastern side of the cutting, approximately half-way between the north-western end of the tunnel and the next bridge across the railway. Here is a continuous section through the *conybeari*, *rotiforme*, *bucklandi*, *gmuendense* and *scipionianum* subzones. The beds are also exposed on the other side of the railway, for some distance north-westwards from the hut, and in places 2–3 ft. of the *sauzeanum* subzone are seen. Above this horizon the succession is obscured, but presumably consists entirely of shales. The total thickness of the beds exposed at Saltford Cutting is about 60 ft., representing almost the whole thickness of the Blue Lias in the district.

Recently the writer has pointed out (1954, p. 6) the difficulty of correlating the section at Saltford, as published by T. Wright, with the one newly measured. This is due principally to the fact that Wright, whose section was measured by Sanders when the cutting was being made, does not give the thicknesses of the individual beds. Wright (1878, pp. 36–7) says that his bed 24 formed the top of the White Lias, and beds 25–30 ('six beds of limestone', which seems too few) should be the basal limestones and shales of the Blue Lias, i.e. the *planorbis* subzone and the lower part of the *johnstoni* subzone, if the 'thick dark shales' below bed 31 mark the base of the Saltford Shales. The top of the Saltford Shales cannot be distinguished, although it must be at about bed 37. The *calcaria* Bed may have been bed 46, in the shale above which is the first record of a bisulcate ammonite. Bed 57 was possibly the *scipionianum* Bed, but the record of '*Arietites conybeari*' from it is puzzling, and seems more likely to refer to a *gmuendense* subzone species of *Coroniceras* (*Primarietites*), in which case bed 57 would be lower; however, the number of limestone beds in Wright's section between his beds 46 and 57 correspond to those between the *calcaria* and *scipionianum* Beds. Further attempts to interpret Wright's records are unprofitable, although an interesting feature, now obscured, is the number of thin limestone beds which occur throughout the Saltford Shales, and particularly the 'Ten beds of shales and limestone, septaria in the lower beds' (bed 34), which are not now visible, about half-way up the Saltford Shales.

**Locality 2: Saltford: Midland Region Cutting** (686678). A shallow cutting on either side of a bridge, half a mile north-north-west of Kelston station, on the line from Bath to Mangotsfield, displays beds of the *semicostatum* zone, and possibly the top of the *bucklandi* zone. Immediately north of the bridge, on the western side of the cutting, about 8 ft. of limestones and shales are exposed. *Paracoroniceras* sp. indet. was found just below the top of the section, indicating a horizon in the upper part of the *gmuendense* subzone, but the rest of the exposure yielded only *Arnioceras* sp. indet., about 3 ft. above the base.

Another exposure lies about 50 yds. south of the bridge on the other side of the cutting, and is continued downwards by an outcrop in the side of the lane which runs beside the cutting. The total thickness exposed is difficult to measure but is about 9 ft. 6 in. The uppermost bed in the cutting contains *Coroniceras* (*Primarietites*) *reynesi* (Spath) in abundance, and fragments of *C.* (*Paracoroniceras*) sp. The ammonites are well weathered out because the bed lies just below the surface of the ground. Here, as in the exposure by the bridge, the remainder of the section has not yielded identifiable ammonites. The greater part of the rocks exposed must fall in the *gmuendense* subzone, but whether the lower part represents the *bucklandi* subzone has not been determined.

**Locality 3: Keeling's Quarry, Keynsham** (659681). This quarry, now disused, lies to the east of the Wells Road at Keynsham, about 100 yds. south of the Bath Road. An analysis of the upper part of the section has been published by Tutcher (1923, p. 272) already, but is repeated here in order to incorporate revised ammonite determinations.

The presence of the Saltford Shales below the section here recorded was proved by a well in the quarry floor. The succession is now visible down to, but not below, the top of bed 23. The upper limit of the *sauzeanum* subzone cannot be determined in the quarry, but *Euasteroceras turneri* (J. de C. Sow.) has been found in temporary excavations in Chandag Road, a few yards to the east. This indicates that the total thickness of the subzone cannot be much greater than the portion exposed in the quarry; i.e. probably not more than 8–10 ft. The section duplicates the Saltford Cutting section from the *angulata* subzone upwards, but the beds are thinner than at Saltford. Ammonite records, taken from Tutcher's account (1923), are placed between square brackets in Fig. 4; the remainder are based on material examined by the writer.

A few remarks may be added on the comparison between Tutcher's and the writer's interpretations of the *bucklandi* and *semicostatum* zones. Tutcher included the shale above the *calcaria* Bed in his *conybeari* subzone; reasons for now placing it in the *rotiforme* subzone are given on page 202. Tutcher placed the lower limit of the *bucklandi* subzone at the base of bed 16 in the section as given here; it is now placed higher (base of bed 14) on account of the absence of any known lower record of *Arietites*, either at Keeling's Quarry or elsewhere in the district. The base of the *gmuendense* subzone is also placed too low by Tutcher; it is not possible to appraise Tutcher's action, as he does not give the exact horizons of

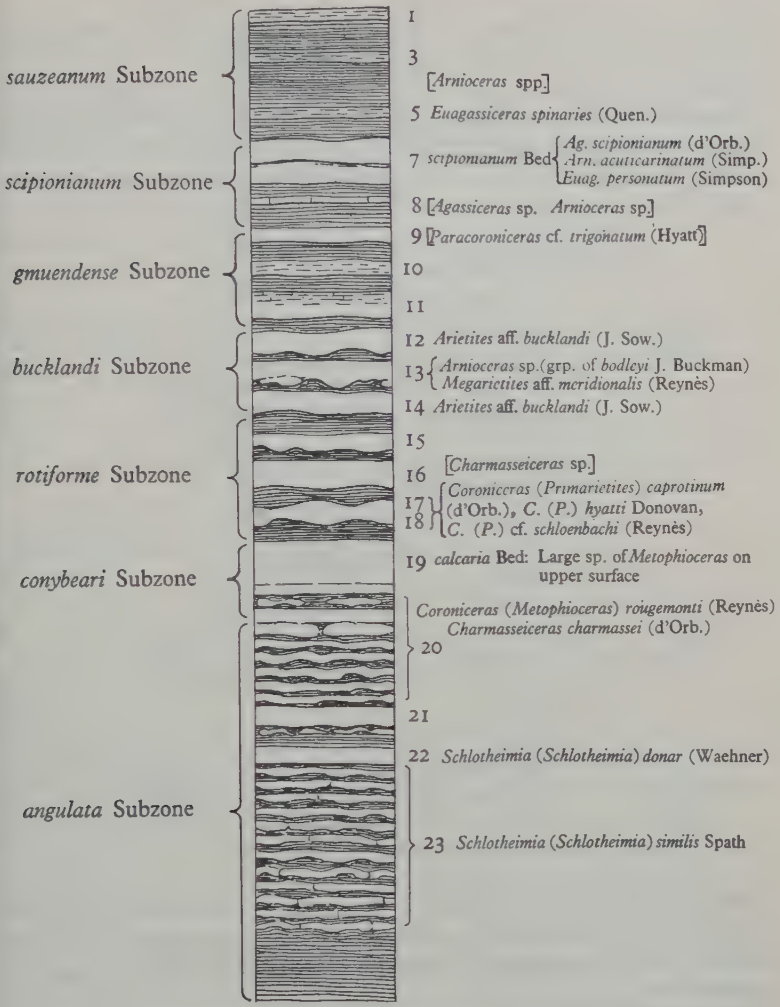
sauzeanum Subzone
scipionianum Subzone
gmuendense Subzone
bucklandi Subzone
rotiforme Subzone
conybeari Subzone
angulata Subzone
1
3
[Arnioceras spp.]
5 Euagassiceras spinaries (Quen.)
7 scipionianum Bed
Ag. scipionianum (d'Orb.)
Arn. acuticarinatum (Simp.)
Euag. personatum (Simpson)
8 [Agassiceras sp. Arnioceras sp.]
9 [Paracoroniceras cf. trigonatum (Hyatt)]
10
11
12 Arietites aff. bucklandi (J. Sow.)
13
Arnioceras sp. (grp. of bodleyi J. Buckman)
Megarietites aff. meridionalis (Reynès)
14 Arietites aff. bucklandi (J. Sow.)
15
16 [Charmasseiceras sp.]
17
18
Coroniceras (Primarietites) caprotinum (d'Orb.), C. (P.) hyatti Donovan, C. (P.) cf. schloenbachi (Reynès)
19 calcaria Bed: Large sp. of Metophioceras on upper surface
Coroniceras (Metophioceras) rougemonti (Reynès)
Charmasseiceras charmassei (d'Orb.)
20
21
22 Schlotheimia (Schlotheimia) donar (Waehner)
23 Schlotheimia (Schlotheimia) similis Spath

Fig. 4. Section at Keeling's Quarry, Keynsham. Vertical scale: 1 in. to 5 ft.

his ammonites within the subzone, but his interpretation places the base (bed 13) well within the range of *Arietites*, and this and the next limestone (bed 12), with *Arietites* aff. *bucklandi* (J. Sow.), are better placed in the *bucklandi* subzone. In the lower part of his *gmuendense* subzone (beds 10–13) Tutcher records two species of *Epammonites*. This genus, which probably belongs to a higher subzone, has not been recognised in the course of the revision of the ammonites from the Blue Lias of the area, and it is probable that Tutcher misidentified late species of the *Primarietites* series, e.g. *Coroniceras* (*Primarietites*) *sublyra* (Spath) or *C.* (*P.*) *reynesi* (Spath).

**Locality 4: Keynsham: St. George's Road** (647685). In 1945 trenches here exposed the *bucklandi* zone, and part of the *semicostatum* zone, yielding a number of large ammonites. The following section was recorded by Mr. T. R. Fry:

| | Bed | ft. | in. |
|---|---|---|---|
| *gmuendense* subzone | 1. Soil, with marly limestone below; *Coroniceras* (*Primarietites*) *reynesi* (Spath) | – | – |
| | 2. Fissile limestone; *C.* (*P.*) *reynesi* | | 7 |
| | Clay | | 2 |
| | 3. Grey limestone with lenticles of clay; *C.* (*P.*) *reynesi*. *Megarietites* aff. *meridionalis* (Reynès) from this bed, or bed no. 4 | | 8 |
| *bucklandi* subzone | Clay | | 3 |
| | 4. Grey limestone; *Arietites bucklandi* (J. Sow.), *Arietites* sp. | | 5 |
| | Limestone | | 4 |
| *rotiforme* subzone | Clay | | 2 |
| | Limestone with clay parting | | 8 |
| | Shale | | 4 |
| | Limestone | | 6 |
| | Clay | | 2 |
| | 5. Limestone in two beds; *Coroniceras* (*Primarietites*) *caprotinum* (d'Orb.) | | 9 |
| | Shale | | 4 |
| | 6. Limestone; *C.* (*P.*) *caprotinum* | | 5 |
| | Shale | | 6 |
| *conybeari* subzone | 7. Dark, blue-grey limestone; the *calcaria* Bed. *Coroniceras* (*Metophioceras*) *rougemonti* (Reynès), *Vermiceras spiratissimum* (Quen.) | 1 | 0 |
| | Rubbly limestone and clay | 1 | 3 |

Above this sequence, elsewhere in the excavations, a bed of limestone 1 ft. 6 in. thick represented the *scipionianum* Bed, but the subzonal fossil was not found. It was succeeded by clay with *Arnioceras* and a fragment of *Euagassiceras*.

This section yielded an abundance of large individuals of *Coroniceras* (*Primarietites*) *reynesi* (Spath) from the *gmuendense* subzone, where they weather out because the beds lie just below the surface, and also a series of well-preserved *C.* (*P.*) *caprotinum* (d'Orb.) from the *rotiforme* subzone.

**Locality 5: Farmborough, Bloomfield Road Quarry** (665600). This quarry is situated on the western side of the road between Farmborough and Timsbury, 350 yds. south of the Butcher's Arms, Farmborough. A considerable area of ground has been quarried, but the only section now visible is a face on the southern side, which is deteriorating. The Sun Bed is visible

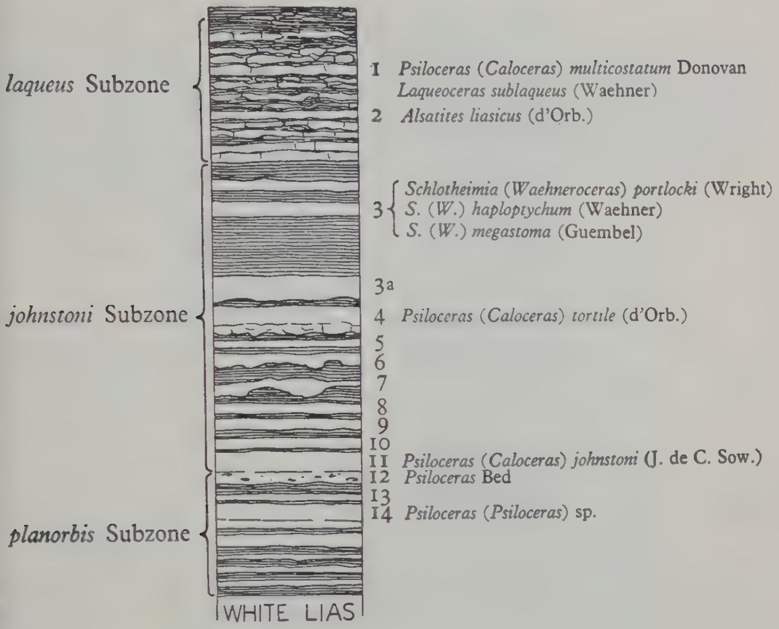
laqueus Subzone
johnstoni Subzone
planorbis Subzone
1 Psiloceras (Caloceras) multicostatum Donovan
Laqueoceras sublaqueus (Waehner)
2 Alsatites liasicus (d'Orb.)
3 Schlotheimia (Waehneroceras) portlocki (Wright)
S. (W.) haploptychum (Waehner)
S. (W.) megastoma (Guembel)
3a
4 Psiloceras (Caloceras) tortile (d'Orb.)
5
6
7
8
9
10
11 Psiloceras (Caloceras) johnstoni (J. de C. Sow.)
12 Psiloceras Bed
13
14 Psiloceras (Psiloceras) sp.
WHITE LIAS

Fig. 5. Section at Bloomfield Road Quarry, Farmborough. Vertical scale: 1 in. to 5 ft.

in one or two places at the bottom, and above it are exposed the basal 15 ft. of the Blue Lias, including the *planorbis*, *johnstoni*, *laqueus*, and perhaps the base of the *angulata* subzones.

The quarry has yielded the only known examples of *Psiloceras* (*Caloceras*) *multicostatum* Donovan, from the *laqueus* subzone, and is one of the few places where *Waehneroceras* may be collected *in situ*. Here the Saltford Shales are reduced to a thickness of 3 ft., and are believed to be represented by the shale below bed 3, and the two shales, separated by a thin limestone bed, above.

Tutcher and Trueman recorded a section at Farmborough in summary form (1925, p. 620). Their records of *Schlotheimia acuticosta* (Strickland) and *S.* cf. *gallica* S. S. Buckman may refer to species of *Waehneroceras*.

**Locality 6: Sutton Hill Quarry, Bishop Sutton** (597586). The quarry, which was worked recently, is on the north side of the road between Clutton and Hinton Blewett, half a mile east of White Cross and half a mile south of Stowey church. Here several feet of the White Lias are exposed, succeeded by about 13 ft. of Blue Lias of the *planorbis* and *johnstoni* subzones. This exposure shows the thickest development in the

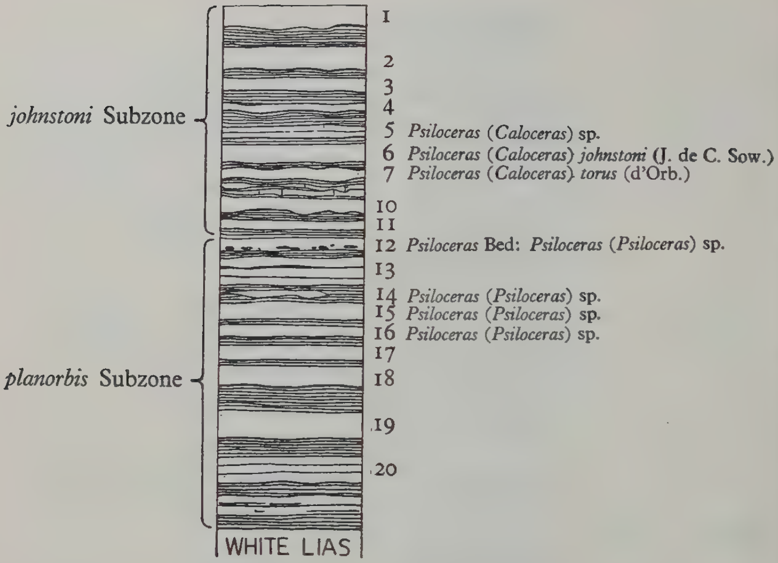
*johnstoni* Subzone
*planorbis* Subzone
1
2
3
4
5 *Psiloceras* (*Caloceras*) sp.
6 *Psiloceras* (*Caloceras*) *johnstoni* (J. de C. Sow.)
7 *Psiloceras* (*Caloceras*) *torus* (d'Orb.)
10
11
12 *Psiloceras* Bed: *Psiloceras* (*Psiloceras*) sp.
13
14 *Psiloceras* (*Psiloceras*) sp.
15 *Psiloceras* (*Psiloceras*) sp.
16 *Psiloceras* (*Psiloceras*) sp.
17
18
19
20
WHITE LIAS

Fig. 6. Section at Sutton Hill Quarry, Bishop Sutton. Vertical scale: 1 in. to 5 ft.

district of the beds between the Sun Bed and the *Psiloceras* Bed, and of the shales and limestones which form the lower part of the *johnstoni* subzone.

**Locality 7: Chewton Keynsham** (649667). An exposure in the *planorbis* zone, important on account of the vertical range of *Psiloceras*: cf. Sutton Hill Quarry (and see p. 198). The section is as follows:

| | Bed | ft. | in. |
|---|---|---|---|
| *johnstoni* subzone | Weathered limestones with *Caloceras* ... ... | – | – |
| | 1. Limestone with *Caloceras* ... ... ... | | 3 |
| | Shale ... ... ... ... ... ... | | 1 |
| | 2. Limestone with *Caloceras* and lamellibranchs... | | 6–7 |
| *planorbis* subzone | 3. Limestone with ferruginous galls: the *Psiloceras* Bed. *Psiloceras* sp. indet. ... ... ... | | 3 |
| | Shale ... ... ... ... ... ... | | 2–3 |
| | 4. Limestone, massive with few joints, with *Psiloceras* sp. indet. ... ... ... ... | | 6 |
| | Shale ... ... ... ... ... | | ½ |
| | 5. Limestone with *Psiloceras* sp. indet. ... ... | | 1 |
| | 6. Limestones and shales ... ... ... ... | 2 | – |
| | White Lias, Sun Bed at top ... ... ... | | – |

**Locality 8: Stowey Quarry** (603593). This quarry lies east of the road leading from Stowey church to the road from Clutton to White Cross and

Hinton Blewett, about half-way between the church and the road-junction. This large old shallow quarry is almost completely overgrown, but two or three beds of limestone are still exposed at the eastern end, and the higher part of the section, recorded below, was exposed by excavation. Of special interest in this section is the condensed deposit of *rotiforme* subzone age, and the abundance of *Vermiceras scylla stoweyense* Donovan, of which it is the principal source. The section is as follows:

| | Bed | ft. | in. |
|---|---|---|---|
| | 1. Blue clay, seen to ... ... ... ... | 1 | – |
| *rotiforme* subzone | 2. Blue-black, soft phosphatic material, lying in hollows in the upper surface of the bed below, with *Coroniceras* (*Primarietites*) *hyatti* Donovan, *C.* (*Metophioceras*) *rougemonti* (Reynès), *Charmasseiceras* sp., *Spiriferina* sp., rhynchonellids, lamellibranchs and gastropods. This bed contains derived ammonites and other fossils. ... ... ... ... | | |
| *conybeari* subzone | 3. Very hard grey limestone with phosphatised fossils; abundant *Vermiceras scylla stoweyense* Donovan ... ... ... ... ... | | about 8 |
| | 4. Hard grey limestone; *Coroniceras* (*Metophioceras*) *caesar* (Reynès), *C.* (*M.*) aff. *deffneri* (Oppel), *C.* (*M.*) aff. *rougemonti* (Reynès) ... ... ... ... ... | 1 | 2 |
| *angulata* subzone | 5. Shale ... ... ... ... ... ... | | 1 |
| | 6. Hard grey limestone ... ... ... ... | | 11 |
| | 7. Shale ... ... ... ... ... ... | | 1 |
| | 8. Limestone, with level top, uneven lower surface | | 2–5 |
| | 9. Shale ... ... ... ... ... ... | | 1–4 |
| | 10. Limestone, with rather soft lower part... ... | | 4 |
| | 11. Limestone, with two partings ... ... ... | | 11 |

Traces of a large schlotheimid ammonite—probably a *Charmasseiceras*—were seen on the upper surface of bed 3. The ammonites in bed 3, although phosphatised, are well preserved and do not appear to be derived, but their condition and abundance probably indicate a slowing-down of normal deposition. Recently bed 3 was assigned to the *rotiforme* subzone (Donovan, 1952, p. 725), but it is now thought more probable that it represents a later part of the *conybeari* subzone than has been preserved around Keynsham and Saltford, as it is succeeded by a remanié bed (No. 2) which includes derived *Metophioceras*. The age and significance of the remanié bed are discussed on page 202. Bed 4 may represent the *calcaria* bed of sections farther north.

**Locality 9: Priston Mill Quarry** (692613). This disused quarry lies about half a mile north of Priston village, on the east side of the lane which leads from the Priston–Marksbury road to a mill, just before the lane crosses a stream. The following section is exposed:

|  | Bed | ft. | n. |
|---|---|---|---|
| *sauzeanum* and ?*scipionianum* subzones | 1. Limestone bed with fragmentary, black, phosphatised fossils in remanié state; *Arnioceras acuticarinatum* (Simpson), *Euagassiceras resupinatum* (Simpson), and brachiopods. Joined to bed below... ... |  | about 6 |
| *gmuendense* subzone | 2. Grey limestone ... ... ... |  | 5 |
|  | 3. Shale ... ... ... ... ... |  | 4 |
|  | 4. Limestone with large *Coroniceras* (*Primarietites*) of *C.* (*P.*) *reynesi* group ... ... ... ... |  | to 11 |
|  | Shale, passing laterally into limestone |  | 4 |
|  | 5. Limestone ... ... ... ... |  | 6 |
|  | 6. Limestone ... ... ... ... |  | 7 |
|  | 7. Limestone ... ... ... ... | 1 | 0 seen |

*Euagassiceras resupinatum* in bed 1 denotes the *sauzeanum* subzone, and *Arnioceras acuticarinatum* usually occurs, in the district, in the *scipionianum* Bed, though it may have a greater range. The *scipionianum* subzone is, therefore, either missing or represented in bed 1. The large fragments of *Coroniceras* in bed 4 are indicative of the *gmuendense* subzone. The condensed sequence, and the reduction of the proportion of shale in it, compared with that at Saltford and Keynsham, marks transition to the conditions applying in the Radstock area (Tutcher & Trueman, 1925).

**Locality 10: Durnford's Quarry, Bedminster Down** (560691). This extensive old quarry lies on the south-eastern side of the main Bristol–Bridgwater road (A 38), just beyond the King's Head Inn. At present the section is visible down to bed 16 only, and the portion below this was recorded by Mr. Fry in 1925. The complete section comprises twenty-two feet of beds. Tutcher (1929, p. 174) records the finding by workmen of a fragment of *Alsatites*, denoting the presence of the *laqueus* subzone which must have been exposed at that time, in the bottom of the quarry. The massive limestone at the top of the section may represent the *calcaria* Bed, of *conybeari* subzone age, but this lithological correlation is unconfirmed as no ammonites have been recorded from this part of the section. Tutcher (*loc. cit.*) may have held the same view, for he says that the quarry shows 'a complete section of the *angulata* beds'.

## 4. BRIEF NOTES ON OTHER SECTIONS

**Locality 11: Manor Road, Keynsham** (663672). This quarry displays the uppermost few feet of the *angulata* subzone (now becoming obscured); the *conybeari* subzone capped by the *calcaria* Bed, and about five feet of limestones with subsidiary shales of the *rotiforme* and *bucklandi* subzones. A considerable area of the upper surface of the *calcaria* Bed, as exposed here,

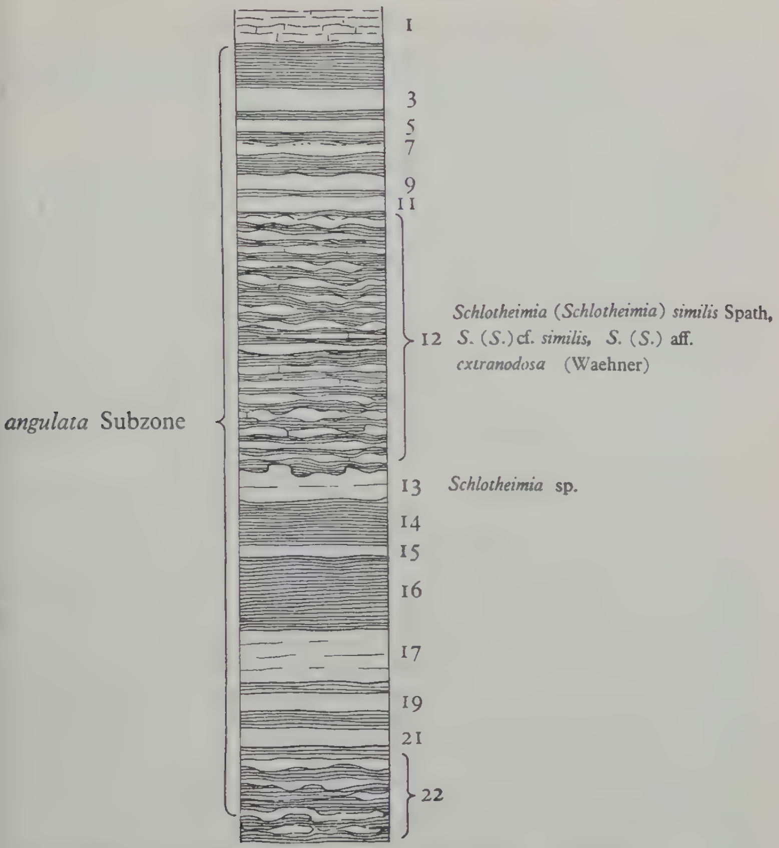
1
3
5
7
9
11
12
Schlotheimia (Schlotheimia) similis Spath, S. (S.) cf. similis, S. (S.) aff. extranodosa (Waehner)
angulata Subzone
13 Schlotheimia sp.
14
15
16
17
19
21
22

Fig. 7. Section at Durnford's Quarry, Bedminster Down. Vertical scale: 1 in. to 5 ft.

was crowded with large individuals of *Metophioceras* cf. *caesar* (Reynès), while occasional *Charmasseiceras* sp., *Arietites bucklandi* (J. Sow.) and *A. quadratum* Donovan occur near the top of the section, about 4 ft. 6 in. above the top of the *calcaria* Bed.

**Locality 12: Kelston Park** (697667). An old quarry in which are exposed about 11 ft. of beds belonging to the *bucklandi* zone, and probably the *semicostatum* zone. A massive limestone bed at the base is probably the *calcaria* Bed. *Arietites* spp. were found at levels 5 ft. and 6 ft. above the top of the basal bed, but no other fossils have been found *in situ*.

**Locality 13: Workshop Covert, Newton St. Loe** (698646). An old quarry, exposing about 11 ft. of beds, in which the *calcaria* Bed can be identified about 3 ft. 6 in. above the bottom of the section.

**Locality 14: Priston** (697606). An old quarry face, on the west side of the stream immediately north of the bridge in the village, where the section extends from the White Lias up to the *angulata* zone, the upper part being poorly exposed. Essentially the succession is similar to that at Farmborough (p. 190).

The Sun Bed, at the top of the White Lias, is succeeded by 2 ft. 6 in. of thin limestones, with subsidiary shale, capped by the *Psiloceras* Bed. This forms the top of the *planorbis* subzone, and is followed by about 3 ft. of limestones with subsidiary shale, belonging to the *johnstoni* subzone. The beds above these become more shaly and ill-exposed, but a reduced representative of the Saltford Shales is probably present, as at Bloomfield Road Quarry, Farmborough. One of the ammonites common to the latter formation, *Laqueoceras* cf. *sublaqueus* (Waehner), has been found in the quarry, but its horizon is not recorded. The section is completed by several feet of limestones and shales in which no diagnostic fossils have been found *in situ*.

**Locality 15: Corston Field Quarry, Corston** (683650). The quarry lies to the south of the road between Corston and Marksbury, three-quarters of a mile from Corston church, and is still worked occasionally. An example of *Alsatites liasicus* (d'Orb.) in the Geological Survey Museum (No. 60142) indicates that the *laqueus* subzone has been exposed at some time in the past. The nine feet of beds visible at present belong to the *angulata* subzone except for a foot or so of massive limestone at the top, which yields fragments of *Metophioceras* and is referable to the *conybeari* subzone. The *angulata* subzone, consisting of thin, alternating shales and limestones, is of interest as having yielded a bisulcate ammonite, of unknown affinities, from a horizon 4 ft. 6 in. below the top of the subzone (Donovan, 1952, p. 748). Other ammonites from this subzone include *Schlotheimia* (*Schlotheimia*) *similis* Spath, *S.* (*S.*) aff. *lymensis* (Spath) and *S.* (*S.*) aff. *pseudomoreana* Spath.

Fossils from the *conybeari* subzone include *Coroniceras* (*Metophioceras*) aff. *deffneri* (Oppel), *C.* (*M.*) aff. *rougemonti* (Reynès), and *Vermiceras scylla* (Reynès).

**Locality 16: Burnett Road Cutting** (665655). A section through the Hettangian was exposed at Burnett along the main road between Keynsham and Marksbury in 1923. The section, now overgrown, was recorded by Mr. T. R. Fry. A summary of this is given below:

| | | ft. | in. |
|---|---|---|---|
| *conybeari* subzone | The *calcaria* Bed. *Coroniceras* (*Metophioceras*) *conybeari* (J. Sow.) ... ... ... ... | 1 | 0 |
| *angulata* subzone | Thinly bedded shales and limestones. *Schlotheimia* (*Schlotheimia*) *donar* (Waehner), *S.* (*S.*) spp. ... | 10 | 0 |

| | | ft. | in. |
|---|---|---|---|
| *laqueus* subzone | Saltford Shales: 9 ft. 6 in. Shale | 1 | 0 |
| | Limestone | | 4 |
| *johnstoni* subzone | Shale | 1 | 6 |
| | Limestone with *Schlotheimia* (*Waehneroceras*) aff. *curviornatum* (Waehner) | 1 | 0 |
| | Shale | 1 | 0 |
| | Limestone | | 4 |
| | Shale | 1 | 0 |
| | Limestone | | 4 |
| | Shale | 3 | 0 |
| | Alternating limestones and shales | 3 | 0 |
| *planorbis* subzone | Alternating limestones and shales | 3 | 0 |
| RHAETIC | White Lias | 5 | 6 |
| | Shales, etc., with *Modiolus langportensis* Richardson & Tutcher | 3 | 9 |
| | Cotham Marble | | 3½ |
| | Cotham Beds: shales with occasional thin limestones | seen 9 | 0 |

The total thickness of the Hettangian here was 25 ft. 6 in., compared with about 41 ft. in the immediate vicinity of Keynsham. The thinning has occurred in the *laqueus* and *angulata* subzones.

**Locality 17: Farmborough** (664606). A small quarry at the junction between the lane which passes the church and the Timsbury road, duplicates the *planorbis* zone of the larger quarry already described (p. 190).

**Locality 18: Harris's Quarry, Marksbury Plain** (655615). A shallow quarry, still worked intermittently. The upper part of the White Lias is succeeded by about 5 ft. of limestones, with subsidiary shale, belonging to the *planorbis* zone. *Psiloceras sampsoni* (Portlock) occurs in an 8 in. bed of limestone, the base of which is 1 ft. 7 in. above the base of the Blue Lias, and above this bed *Psiloceras* sp. and *Caloceras johnstoni* (J. de C. Sow.) are found.

**Locality 19: Compton Dando** (664638). A disused quarry 400 yds. west-south-west of Wansdyke House. The *Psiloceras* Bed, 6 in. thick, is separated from the Sun Bed at the top of the White Lias by 1 ft. 10 in. of limestones with subsidiary shales, and is succeeded by about 2 ft. of beds with *Caloceras*.

**Locality 20: Compton Dando, Wick Farm Quarry** (650632). Here the lower part of the *planorbis* zone is exposed. The base of the *Psiloceras* Bed is 1 ft. 10 in. above the top of the White Lias.

**Locality 21: Knowle West** (area around 590700). This district, now built over, was interesting as showing the thickest development of the *planorbis* subzone. Between 1926 and 1929 quarries on Novers Hill showed about 7 ft. of thinly-bedded limestones and shales between the top of the White Lias and the *Psiloceras* Bed. The 'East Quarry' yielded a specimen of *Psiloceras* (*Franziceras*) aff. *ruidum* (S. S. Buckman) from a level about 5 ft. above the base of the *Psiloceras* Bed (see Donovan, 1952, p. 641).

**Locality 22: Headley Park** (approx. 575691). The Liassic succession was observed during the development of this suburb of Bristol in 1938. The *Psiloceras* Bed lay 6–7 ft. above the base of the Blue Lias series. Higher in the sequence, about 20 ft. of shales, identified as the Saltford Shales, were exposed. They yielded *Schlotheimia* (*Waehneroceras*) *portlocki* (Wright).

## 5. GENERAL ACCOUNT OF THE STRATIGRAPHY

**Planorbis subzone.** In many places the upper surface of the White Lias is penetrated by U-shaped borings, and, after this slight hiatus in sedimentation, beds of a different character were laid down. The succeeding limestones and shales occur in thin and rather irregular beds, with a characteristic fauna of lamellibranchs (Tutcher, 1908, p. 6; Kellaway, 1931, p. 300), though where the series thickens the limestones tend to be thicker, more even, and with fewer fossils. Frequently the beds have been exposed as overburden during quarrying for White Lias, and may be seen at a number of places (Localities 5, 6, 7, 14, 17, 18, 19, 20). The first constant horizon in the Blue Lias which can be recognised throughout the area is the *Psiloceras* Bed,[1] a limestone bed, 3 in. to 8 in. thick, usually with ferruginous galls, in which *Psiloceras* is locally abundant. *P. plicatulum* (Quen.) *bristoviense* Donovan is the common species in this bed, but *P. sampsoni* (Portlock) is found at some localities.

The *Psiloceras* Bed does not mark the first or only appearance of the genus, as has been supposed (Vaughan & Tutcher, 1903, p. 15; Tutcher, 1923, p. 276); examples have been found in lower beds at several sections (Localities 5, 6, 7) and the base of the *planorbis* subzone can no longer be put at the *Psiloceras* Bed. The only satisfactory alternative is to fix the base of the subzone at the base of the Blue Lias formation, thus disposing of the old pre-*Planorbis* Beds or *Pleuromya* and *Ostrea liassica* Beds (Tutcher, 1908, p. 6) as a separate 'zone', although the term *Ostrea* Beds may still be used for that part of the *planorbis* subzone below the *Psiloceras* Bed. In north Somerset the *Ostrea* Beds vary considerably in thickness. Around Marksbury they are thinnest, being only 1 ft. 10 in. (Localities 18, 19, 20), but thicken to from 3 ft. to 4 ft. south of the Farmborough fault zone, and north of the Burnett fault zone. Westwards from the Farmborough area there is an abrupt thickening to 7 ft. at Sutton Hill Quarry (Locality 6), and a similar development is also present in the southern suburbs of Bristol (Localities 21, 22).

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[1] Name proposed to replace *Planorbis* Bed of Vaughan & Tutcher (1903, p. 37), as the species *Psiloceras planorbis* does not occur in the bed.

**Johnstoni subzone.** The *Psiloceras* Bed forms the top of the *planorbis* subzone, and is usually succeeded immediately by the *johnstoni* subzone. A limestone bearing *Psiloceras* (*Caloceras*) *johnstoni* is sometimes joined to the top of the *Psiloceras* Bed (Localities 5, 7, 17, 19). The limestones and shales of the lower part of the *johnstoni* subzone are similar to those of the preceding subzone; at some exposures they are characterised by an abundance of *Lima gigantea* (J. Sowerby). Their combined thickness in the Keynsham area is usually 3 ft. 6 in., but south of Bristol they reach 6 ft. or more.

The upper part of the *johnstoni*[1] subzone consists of shales which constitute the principal interruption in the regular alternation of shale and limestone beds of the Blue Lias. The shales are named the Saltford Shales, after their only permanent exposure at Saltford cutting (Locality 1), where they are about 17 ft. thick, including 3 ft. at the top which belong to the *laqueus* subzone. The section at Saltford is not sufficiently good for a detailed determination of the succession to be made in the shales, but the fresh exposure at Keynsham Hams showed beds of limestone, usually not more than 6 in. thick, at fairly regular intervals throughout (Tutcher, 1923, p. 275). It is probable that the beds labelled '*liasicus* zone' in Tutcher's section, with the exception of the uppermost 2 ft. 4 in., represent the Saltford Shales. The only fossil horizon in the part of the Saltford Shales which belongs to the *johnstoni* subzone is a bed with several species of *Waehneroceras*, situated 4 ft. 4 in. below the top of the shales at the type locality (bed 23). A possible *Waehneroceras* was recorded from Keynsham Hams by Tutcher (1923, p. 276). At Farmborough (Locality 5), four and a half miles south of Saltford, the limestones and shales with *Caloceras*, forming the lower part of the subzone, are normally developed, but above this level the succession is much reduced in thickness, and the Saltford Shales are probably represented by 3 ft. of shales, with two limestone bands, which rest on bed 3a. The lower limestone (bed 3) has yielded several species of *Waehneroceras*. South of Bristol, the Saltford Shales were exposed in a bomb crater on Bedminster Down (where *Waehneroceras* was obtained), and in excavations at Headley Park (Locality 22). Their thickness, in this area, is believed to be about twenty feet.

The sections of Vaughan & Tutcher (1903) do not show the Saltford Shales, which appear to have been overlooked. In the section at Kelston Station (*op. cit.*, p. 36) the *johnstoni* subzone is succeeded by six feet of clays, with two beds of limestone, the upper of which yielded '*Am. angulatus*' [?*Waehneroceras*]. The clay was capped by 'a thin series of limestones much broken up by the downgrowth of roots' (*op. cit.*, p. 38) said to belong to the upper part of the *angulata* [sub]zone. On the basis of the information given by Vaughan & Tutcher it is impossible either to agree, or to disagree, with their interpretation, which involves the almost complete disappearance of the Saltford Shales, and the limestones and shales of the lower part of the *angulata* subzone, in a distance of less than half a mile to the east of Saltford Cutting.

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[1] *Caloceras johnstoni* does not occur in this part of the subzone. See p. 211.

Above the limestones of the lower *johnstoni* subzone Vaughan & Tutcher recognised an horizon, with abundant echinoid fragments, which they named the Echinid Bed (1903, p. 15). In point of fact, echinoid remains occur at several horizons in the Saltford Shales, and in the clays of the *angulata* zone, thus rendering it inadvisable to use the term for a stratigraphic unit. In their composite section 'North of Keynsham' Vaughan & Tutcher (*op. cit.*, p. 24) show the Echinid Bed as alone separating the *johnstoni* beds (i.e. the limestones at the base of the *johnstoni* subzone, as described on p. 199) from the *Ostrea irregularis* beds (base of the *angulata* subzone of this paper), the omission of the Saltford Shales being possibly due to the failure to recognise the existence of echinoid remains at more than one level.

**Laqueus subzone.** The highest limestone bed (22a) in the Saltford Shales of the type locality yielded *Laqueoceras laqueus* (Quen.), and marks the base of the *laqueus* subzone. The subzonal index fossil has also been found at Bedminster (Donovan, 1952, p. 642), and an ammonite, recorded by Tutcher from Keynsham Hams (1923, p. 275) as '*Psiloceras crebricinctum* Waehner?', was probably a *Laqueoceras*. The Saltford Shales at Saltford are succeeded by about half a dozen beds of limestone with thin shale partings, about 2 ft. 6 in. in thickness, and containing *Alsatites liasicus* (d'Orb.) (bed 22). The same beds were seen at the base of the Railway Siding section at Keynsham Hams (Tutcher, 1923, p. 274), where the lowest three beds of limestone exposed are probably a partial equivalent of bed 22 at Saltford Cutting.

The subzone is not well-defined except at Keynsham and Saltford; at Farmborough (Locality 5) it is thinner, amounting to about 3 ft. of limestones and shales. *Laqueoceras sublaqueus* (Waehner) has been found here, but not *Alsatites*. At Corston Field (Locality 15) *Alsatites* has been found (Donovan, 1952, p. 644), but the *laqueus* subzone is not exposed at present. *Alsatites* has also been recorded from Bedminster Down (Locality 10).

Neither *Laqueoceras*, nor *Alsatites*, was recorded from the Willsbridge and Kelston sections by Vaughan & Tutcher, whose section at Kelston has already been referred to (p. 199); the apparent absence of these fossils may be due to non-exposure of the *laqueus* subzone.

**Angulata subzone.** The subzone consists principally of irregular, nodular limestones, alternating with shales, in thin beds—the 'thin disjointed limestones' of Vaughan & Tutcher (1903, p. 25), interspersed with one or two thicker bands of clay, and a few more regular beds of limestone. Where the subzone is thickest there are two groups of nodular limestones, the upper slightly more regular than the lower, separated by a bed of shale. The lower series of nodular limestones is the *Ostrea irregularis* series of Vaughan & Tutcher (1903, p. 25). The upper series forms the lower part of the *Calcicosta* series of the same authors, and the shale between the two series is the 'conspicuous band of clay' of their description. At Keeling's Quarry, Keynsham (Locality 3), the two groups are beds 20 and 23, separated by a shale which is sandwiched between two massive limestones (beds 21 and 22). At Saltford Cutting (Locality 1) beds 17 to 19 form the lower group, and bed 15 forms the upper group, again separated by a shale (bed 16) between two persistent limestones. At Willsbridge, only the top of the upper nodular series is now seen (beds 9–12; Donovan, 1948, p. 337), but when the section was measured by Vaughan & Tutcher the whole of the subzone was exposed, the shale between the two nodular limestone series at the other exposures being probably that lying opposite the letter 'M' of *Am. angulatus* in their diagram (1903, p. 24).

At Durnford's Quarry, Bedminster Down (Locality 10), beds 17–22 represent the lower limestones, and bed 12 the upper limestones. The intervening shales (beds 14, 16) yield echinoid-debris.

No palaeontological subdivision of the subzone can be established satisfactorily. The lower part is characterised by *Schlotheimia similis* Spath, the lower nodular limestones having yielded good examples of this species at Keeling's Quarry, Keynsham, and fragments of the same elsewhere. *Schlotheimia pseudomoreana* Spath probably occurs principally in the upper part of the subzone, but most of the ammonites from this part of the succession are fragments of outer whorls of large schlotheimids which cannot be identified specifically. *Charmasseiceras* appears just below the top of the subzone at Keynsham.

**Conybeari subzone.** The most conspicuous, and only persistent, stratum in this subzone is the *calcaria* Bed,[1] a massive bed of limestone which forms the upper part of the subdivision, and is often exposed (Localities 1, 3, 4, 11, 13, 16). At most exposures species of *Metophioceras*, the subzonal ammonite, are found in one or two beds of limestone below the *calcaria* Bed. These limestones are indistinguishable, lithologically, from the underlying beds of the *angulata* subzone. The total thickness of the subzone is only about two feet. The *calcaria* Bed is usually about 1 ft. 3 in. thick, although it is variable, and at Manor Road Quarry, Keynsham (Locality 11), is only seven inches. The upper surface of the bed yields large ammonites of the genera *Metophioceras* and *Charmasseiceras*. When this surface is laid bare by quarrying these genera are sometimes seen to be very numerous, as was the case, recently, at Manor Road Quarry.

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[1] Name used by the author (1948, pp. 336–7) to replace '*calcicosta* Limestone' of earlier authors, e.g. Tutcher, 1923, p. 271.

The *calcaria* Bed forms the present top of the subzone throughout the area, but higher beds were laid down, and subsequently destroyed, and their remains incorporated in the condensed, or remanié, deposits at the base of the *rotiforme* subzone.

**Rotiforme subzone.** At the majority of exposures the *calcaria* Bed is succeeded by a remanié bed which appears to have resulted from the reworking of later deposits of *conybeari* age. At Willsbridge (Donovan, 1948, p. 337), *Coroniceras* (*Primarietites*) *rotiforme* (J. de C. Sow.) is found at the top of the *calcaria* Bed, beneath the remanié bed, and as the remanié bed itself contains *Primarietites*, as well as fossils of the *conybeari* subzone, the reworking is believed to have occurred in *rotiforme* subzone times. It may be that the destruction of the upper part of the *conybeari* subzone, as originally deposited, came to a halt at the massive *calcaria* Bed. Vaughan & Tutcher (1903, p. 24) noted the main elements of the fauna of the remanié bed at Willsbridge when they recorded from it '*Am. rotiformis*, *Am. charmassei* and *Am. conybeari*' in their vertical section, but although they remarked that it was 'very rich in fossils' (*op. cit.*, p. 31) they did not notice its condensed nature. In fact the bed (the lowest bed of the 'Zone of Am. arietes' in Vaughan & Tutcher's section; bed 6 of Donovan, 1948, p. 337) is an impure sandy clay, with phosphatic nodules and lumps of limestone, as well as the ammonites. These last occur as phosphatic internal moulds and include several species of *Charmasseiceras*, several species of *Metophioceras*, and *Coroniceras* (*Primarietites*) *schloenbachi* (Reynès).

The remanié bed was clearly present in the Railway Siding section at Keynsham Hams (Tutcher, 1923, p. 274), although here again its special features were unnoticed. Tutcher found *Charmasseiceras* ('*Schlotheimia* cf. *charmassei*'), *Metophioceras* ('*Vermiceras* cf. *conybeari*'), and probably *Primarietites* (?'*Coroniceras* cf. *cordieri*'). The remanié bed was exposed in a temporary exposure at Weston, Bath (Donovan, 1948, p. 336, bed 20), where it filled hollows in the upper surface of the *calcaria* Bed.

South of the Avon, at Saltford (Localities 1, 3, 4, 11), the remanié bed does not occur, but it is unlikely that the succession here is any more complete, as the *calcaria* Bed is succeeded abruptly everywhere by beds with *Primarietites*.

In addition to the remanié bed, wherever it is present, the *rotiforme* subzone includes all the beds between the *calcaria* Bed and the first appearance of *Arietites*. At Saltford Cutting (Locality 1) no ammonites were obtained, but Keeling's Quarry, Keynsham (Locality 3) yielded *Coroniceras* (*Primarietites*) *caprotinum* and *C.* (*P.*) *hyatti* from the lowest limestone bed in the subzone, and the first-named species was also common in the two lowest beds of limestone in the subzone at St. George's Road, Keynsham

(Locality 4). At these sections *C.* (*P.*) *rotiforme* and the allied *C.* (*P.*) *schloenbachi* have not been found, and it is probable that the remanié bed, with which these two species are associated elsewhere, is represented at Keynsham by a non-sequence. The uppermost part of the subzone has not yielded ammonites.

A condensed deposit (bed 2) at Stowey Quarry (Locality 8) includes later elements than those in the remanié beds farther north. The predominant ammonite is *Coroniceras* (*Primarietites*) *hyatti* Donovan, and the earlier group of *C.* (*P.*) *rotiforme* is absent. *Coroniceras* (*Metophioceras*) *rougemonti* (Reynès) has also been found, however, in the Stowey bed, which rests in hollows in a massive bed of limestone (bed 3) which may be the equivalent of the *calcaria* Bed. It may have been formed, therefore, by the destruction of *conybeari* subzone deposits at a slightly later date than the remanié beds of Willsbridge and Bath.

**Bucklandi subzone.** *Arietites bucklandi* is a well-known ammonite, but the horizon in the succession at which it appears has only been observed at Saltford Cutting, at Keeling's Quarry and at St. George's Road, Keynsham (Localities 1, 3, 4). At both the Keynsham exposures it is first found about 4 ft. above the top of the *calcaria* Bed; at Saltford, where the beds above the *calcaria* Bed are slightly thicker, the corresponding interval is about 5 ft. The subzone, which has a maximum thickness of about 2 ft., is not lithologically demarcated from the beds above and below, nor is there any marker horizon within it which can be used to correlate one section with another. In addition to *Arietites*, the subzone yields occasional examples of *Megarietites*, and *Arnioceras* enters the succession at this level.

**Gmuendense subzone.** The characteristic feature of this subzone at some localities is the abundance of large individuals of *Coroniceras* (*Primarietites*) *reynesi* (Spath), and allied forms, as at St. George's Road, Keynsham (Locality 4), and the Midland Region Cutting, Saltford (Locality 2). *Megarietites* ranges up into the lower part of the subzone. *Paracoroniceras*, the subzonal index fossil, occurs sparingly, and only fragments have been recovered *in situ*; *Arnioceras* is present throughout. The thickness of the subzone is 7 ft. at Saltford Cutting, but only 3 ft. at Keeling's Quarry, Keynsham.

**Scipionianum subzone.** *Agassiceras scipionianum* (d'Orb.) is known to the writer from only one horizon, the *scipionianum* Bed (which is bed 7 at Keeling's Quarry, Keynsham), but the underlying shale is also included in this subzone on account of Tutcher's record (1923, p. 272) of '*Aetomoceras* [*recte Agassiceras*] sp. indet.' On lithological grounds the bed is identified as bed 1 at Saltford Cutting, but the characteristic ammonite has not been found there. The bed was also exposed at the Sewage Works at Keynsham, where a number of examples of *Agassiceras* were obtained in 1930. Associated with this genus at Keynsham and Saltford are *Arnioceras acuti-*

*carinatum* (Simpson) and *Euagassiceras personatum* (Simpson). Usually the fossils in the *scipionianum* Bed are phosphatised, and some condensation of the sequence has taken place at this level.

**Sauzeanum subzone.** At Keeling's Quarry, Keynsham (Locality 3), the clays and marls above the *scipionianum* Bed have yielded *Eugassiceras spinaries* (Quen.), and Tutcher also records '*Agassiceras* [*recte Euagassiceras*] cf. *sauzeanum* . . . *A*. sp. nov.' and several species of *Arnioceras*. Corresponding beds are present at Saltford Cutting (Locality 1), where a specimen of *E. spinaries* (Quen.) was obtained. The upper limit of the subzone has not been defined, but the thickness visible at Keynsham is about 5 ft., and probably the whole subzone is not much thicker (see p. 188).

At Priston Mill Quarry (Locality 9) limestones of the *gmuendense* subzone are capped by a limestone bed containing fragmentary, phosphatised fossils, including the ammonites *Arnioceras acuticarinatum* (Simpson) and *Euagassiceras resupinatum* (Simpson). Around Keynsham the first-named species occurs in the *scipionianum* Bed, and its association with *Euagassiceras resupinatum* (Simpson) in a remanié bed may indicate that the condensation of the sequence marked by the *scipionianum* Bed at Keynsham also included the *sauzeanum* subzone at Priston. Thus the locality marks the approach to the Timsbury area where the *semicostatum* zone, in so far as it is present at all, is represented by the '*Bucklandi* Bed', 1 ft. 2 in. thick (Tutcher & Trueman, 1925, p. 605).

**General Remarks.** The sections studied show that the Blue Lias is subject to considerable lateral variation in the thicknesses of its component subzones. No attempt has been made to present a general picture of this variation, as the writer believes that such a picture, based on the evidence now available, would be too simple. Broad trends are clear, however. The transition to the Radstock area to the south, with its much more condensed sequence, is shown at Farmborough, Priston and Stowey, where exposures of different parts of the succession all reveal thinning. Even where the development is fullest, at Keynsham and Saltford, condensation of the sequence has occurred at two levels, marked by the remanié bed above the *calcaria* Bed and by the *scipionianum* Bed while the *Psiloceras* Bed may also mark a slowing-down of deposition.

The thinnest development of the *Ostrea* Beds is found in an east–west belt between the Burnett faults, traceable in the Lias outcrop (Cox, 1941, p. 18), on the north, and the Farmborough and Temple Cloud faults, traceable in the Palaeozoic rocks (Moore & Trueman, 1939, p. 57), on the south. These fault-zones may have bounded an elevated area of the seafloor at the commencement of Liassic times, although the downthrow of the Burnett faults, in the Mesozoic rocks, is southerly, and that of the Farmborough and Temple Cloud faults seems to be uncertain.

The Saltford Shales are too rarely exposed for their variation to be traced in detail, but a southerly thinning is seen at Burnett (Locality 16) and the thin, nodular limestones of the *angulata* subzone show similar attenuation. With regard to the *bucklandi* and *semicostatum* zones it has not been possible to follow the transition from Keynsham and Saltford (where the zones are represented by up to 21 ft. of regularly alternating limestones and shales) southward to the Radstock area, where they are represented by a few inches of deposits, at the most, since no intervening exposures have been found. The absence of any sections in these zones in the country around Marksbury may indicate that the shale and limestone development is absent from this area also.

## 6. COMPARISON WITH OTHER AREAS

Comparison is made with two other well-known sections in the south of England: at Lyme Regis, Dorset, and on the Glamorgan coast, South Wales. Extensive comparison might also be made with recently-published successions in France, Germany and Switzerland, but this is outside the scope of the present work.

**Dorset (Lyme Regis).** The Blue Lias of Lyme Regis is thicker than it is in the Keynsham area, but essentially it is similar in development, especially in the lower part. Lang (1924, p. 172) measured a thickness of 96 ft. 7 in.—less than the total given by H.M. Geological Survey—while at Saltford Cutting the total thickness exposed is about 60 ft., to which probably not more than 4–5 ft. need be added, to allow for the unexposed basal part. The total thickness at Saltford is, therefore, almost exactly two-thirds of that at Lyme Regis. The increased thickness of the Lyme Regis section falls mainly in the *bucklandi* and *semicostatum* zones, but the Hettangian, although of similar thickness at both localities (about 42 ft. near Keynsham and 44 ft. 8 in. at Lyme Regis), differs considerably in the thicknesses of its different subzones.

The *planorbis* zone at Lyme Regis is 28 ft. 1 in. thick, about 5 ft. thicker than the maximum at Keynsham and Saltford, and includes 8 ft. 2 in. of *Ostrea* beds between the White Lias and the earliest *Psiloceras*. The species of *Psiloceras* recorded from Lyme Regis (*P.* cf. *plicatulum* and *P.* cf. *sampsoni*) are suggestive of the forms found around Keynsham (Donovan, 1952, pp. 635–7). The upper part of the zone is known in considerably more detail at Lyme Regis than it is at Keynsham. It was divided by Lang into three 'zones', characterised (from below upwards) by *Caloceras*, *Waehneroceras* and *Psilophyllites*. *Waehneroceras*, restricted to one horizon around Keynsham, occurs in several beds at Lyme Regis, but unfortunately the Lyme Regis ammonites were generally too poor to be identified specifically, and *Psilophyllites* has not been found in the Keynsham area. It occurs at Lyme Regis in association with *Waehneroceras*, and its absence from Keynsham and Saltford, coupled with the more restricted range of *Waehneroceras*, may indicate a non-sequence in the succession somewhere between the horizon involving *Waehneroceras* and that characterised by *Laqueoceras*, approximately equivalent to the *Psilophyllites hagenowi* zone at Lyme Regis.[1]

*Alsatites*, as here restricted,[2] has not been found in the coastal sections of Lyme Regis, but a substantial thickness of beds was allotted to a *liasicus* zone. In Lang's section the base of this zone is marked by an abrupt increase in the frequency of limestone bands in the succession, and by the irregular character of the limestones ('limestones with undulating surfaces' in Lang's description) compared with those in the underlying part of the succession. This lithological change is reminiscent of that which occurs at the top of the Saltford Shales at Saltford. The upper part of Lang's *liasicus* zone, however, contains *Schlotheimia similis* Spath and corresponds to the lower part of the *angulata* subzone at Saltford and Keynsham. The total thickness of the thin, irregular limestones of the *laqueus* and *angulata* subzones is 16 ft. at Saltford Cutting, and 14 ft. 4 in. at Lyme Regis (beds H.73 to 15 inclusive), although it is possible that some of the beds placed by Lang in the lower part of the *conybeari* subzone are equivalent to beds allotted to the *angulata* subzone at Keynsham. At this horizon at Lyme Regis (bed 18), there is a development of shales and marls, without ammonites, which has no recognisable equivalent at Saltford or Keynsham. The sequence of species of *Schlotheimia* at Lyme Regis is comparable with that at Keynsham; *S. similis* Spath and the allied *S. phoenix* Spath are reported from the lower part of the subzone (upper part of the *liasicus* zone in Lang's notation), and *S. pseudomoreana* Spath, together with other species, from the upper part (the *marmorea* zone of Lang).

No close comparison is possible between representatives of the *bucklandi* zone in the two areas, although the change from thin, irregular limestones to thicker, more regular beds occurs at the base of the zone in both areas. The *conybeari* subzone is more fully developed at Lyme Regis than at Saltford; 9 ft. 3 in. of beds are allotted to the subzone by Lang, and although only 2 ft. 9 in. of the succession contains *Metophioceras*, this is greater than the range of the subgenus at Keynsham. It is tempting to recognise in the 'Top Tape' at Lyme Regis (bed 29), with its 'upper surface crowded with *Metophioceras* spp.', the equivalent of the *calcaria* Bed in the

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[1] On the other hand, it is not impossible that *Psilophyllites* may yet be found in the Bristol–Keynsham district. It is a small and inconspicuous fossil, and the horizon at which it would be expected to occur is seldom well-exposed. The evidence for *Waehneroceras*, an easily-recognisable ammonite the presence of which is now well-established in the area, was still 'inconclusive' when Tutcher wrote his important paper of 1923.

[2] In 1924 it included species now referred to *Laqueoceras*.

Keynsham area, but perhaps unwise to suggest the identity of an individual bed over such a distance. Except for the concentration of ammonites on the upper surface of 'Top Tape', there is no evidence at Lyme Regis for the condensation of part of the upper *conybeari* and lower *rotiforme* subzones, such as occurred at Keynsham.

The *rotiforme* subzone is much thicker at Lyme Regis (11 ft. 9 in.) than it is around Keynsham (about 4 ft.). Upwards from this subzone the succession is not only much more shaly at Lyme Regis than it is at Keynsham, but it is substantially thicker at the former locality than it is at the latter. The earliest ammonite recorded in the subzone at Lyme is *Coroniceras* (*Primarietites*) *schloenbachi* (Reynès), which occurs in the basal remanié deposit at Willsbridge. The record of *Arnioceratoides* by Lang from bed 36b may indicate a form comparable to *C.* (*P.*) *hyatti* Donovan, the inner whorls of which sometimes resemble '*Arnioceratoides*' (*recte Coroniceras* s.s.), and which occurs about the middle of the subzone at Keynsham.

Above the highest *Primarietites* (*Coroniceras* in Lang's paper) at Lyme Regis are 11 ft. 4 in. of shales, with subsidiary limestone bands but no ammonites except *Charmasseiceras*. These beds were included by Lang in a combined zone of '*Paracoroniceras gmuendense* and *Coroniceras bucklandi*', which he was unable to differentiate. The ammonite records from this part of the succession at Lyme Regis are exceptionally meagre, and while *Arietites* apparently occurs (Spath, 1924, p. 205), the only genera found *in situ* by Lang were *Paracoroniceras* and *Arnioceras*. The combined zones at Lyme Regis are 16 ft. 6 in. thick, compared with about 6 ft. at Keynsham and 10 ft. at Saltford for the approximately corresponding part of the succession, but no further comparison is possible. Spath has noted the absence of *Megarietites* from Lyme Regis (*op. cit.*, p. 204), and the late *Primarietites* (*P. reynesi* (Spath), *P. multicostatus* (J. de C. Sow.), etc.), are likewise unknown. The absence of records of these forms may be due partly to collection failure and partly to the former practice of identifying any large ammonite from about this horizon as *Amm. bucklandi*, but even when allowance is made for these factors, the fauna seems to be poorer. There are no obvious signs of non-sequence in the thicker Lyme Regis succession, and the absence of the abundant large ammonites of the *gmuendense* subzone at Keynsham may be due to a lithology less favourable to their preservation.

The *scipionianum* subzone at Keynsham is represented by a single limestone bed, perhaps together with the underlying shale, while at Lyme Regis *Agassiceras* ranges through about 8–9 ft. of beds, mainly shales. The *scipionianum* bed at Keynsham is a condensed deposit which may represent part or all of the 'Zone of "*Aetomoceras*" *scipionianum*' at Lyme, but the fossil records from the latter, mostly based on poorly-preserved material, do not allow of a close comparison between the two occurrences. *Arnioceras acuticarinatum* (Simpson), which accompanies *Ag. scipionianum* (d'Orb.) in the Keynsham area, has not been identified from Lyme Regis, but the species of *Euagassiceras* recorded by Lang and identified by Spath mainly from crushed material, may or may not be as different as the list of qualified attributions suggests from the Keynsham and Bristol forms. On account of the more shaly nature of the *rotiforme* and subsequent subzones, the abrupt and almost complete disappearance of limestones from the succession, which occurs above the *scipionianum* Bed around Keynsham, is not a feature of the Lyme succession.

The shales above the *scipionianum* Bed at Keynsham yield *Euagassiceras spinaries* (Quen.). An ammonite recorded as similar to this species occurs at Lyme Regis in beds 52d and 52f, in the upper part of the range of

**Palaeontological subdivisions of the Blue Lias employed by different workers**

| Subzones used in present paper | Zones of W. D. Lang, 1924 | Subdivisions of A. E. Trueman, 1920, 1930 |
|---|---|---|
| *sauzeanum* | *scipionianum* | |
| *scipionianum* | | |
| *gmuendense* | *gmuendense* and *bucklandi*, undifferentiated | *gmuendense* and *bucklandi*, undifferentiated |
| *bucklandi* | | |
| *rotiforme* | *rotiforme* | *rotiforme* subzone |
| *conybeari* | *conybeari* | *conybeari* subzone |
| *angulata* | *marmorea* | *angulata* beds |
| *laqueus* | *liasicus* | |
| | *laqueus* | |
| *johnstoni* | *hagenowi* | |
| | *portlocki* | *Waehneroceras* beds |
| | *johnstoni* | *johnstoni* beds |
| *planorbis* | *planorbis* | *planorbis* beds |
| | *Ostrea* | *Ostrea beds* |

*Agassiceras*, but in the absence of an unqualified record of the species no equivalence between the beds at Lyme Regis and at Keynsham can be suggested. Bed 52f at Lyme Regis contains several ammonite species, including *Arnioceras miserabile*, *A.* cf. *nodulosum* (Quen.), and *Agassiceras* cf. *colesi* (J. Buckman), which are not known from Keynsham, and it is more probable that bed 52f at Lyme Regis, and perhaps some of the underlying strata, are represented at Keynsham by a non-sequence above the *scipionianum* Bed. On the other hand, the beds at Keynsham with *Eu. spinaries* (Quen.), may belong to a part of the succession unrepresented at Lyme Regis. Alternatively, their apparent absence there may be due to the absence of the characteristic ammonite, or to collection-failure.

The topmost member of Lang's Blue Lias succession, a limestone placed by him in a zone of *Arnioceras pseudokridion*, which has not been generally recognised, may be represented by shales on Bedminster Down containing *Arnioceras* very similar to *A. pseudokridion* Spath. On the other hand, the similarity may be due partly to the fact that the specimens are crushed in both cases.

**Glamorganshire.** Detailed accounts of the lowest zones of the Lias on the Glamorganshire coast have been published by Trueman (1920, 1922, 1930). Where typically developed, away from the well-known littoral facies of South Wales, the series is much thicker than at either Keynsham or Lyme Regis, and no detailed lithological similarities can be recognised.

The *Ostrea* Beds in Glamorgan are 21 ft. thick (Trueman, 1920, p. 100), and are succeeded by 4 ft. 8 in. of beds with both plicate and smooth species of *Psiloceras*. Above these, *Caloceras* ranges throughout 24 ft. 11 in. of strata. The lower part of this range yields *Psiloceras* (*Caloceras*) cf. *johnstoni* (J. de C. Sow.) and the allied *P.* (*C.*) *intermedium* (Portlock) and *P.* (*C.*) cf. *torus* (d'Orb.). In the upper part of its range *Caloceras* overlaps with *Waehneroceras*, but as specific identifications were not given by Trueman, comparison cannot be made with Somerset, where *P.* (*C.*) *multicostatum* Donovan, a species so far unrecognised elsewhere, occurs above *Waehneroceras*. *Waehneroceras*, confined to a single horizon around Keynsham, has a range of at least 6 ft., and probably more, at Glamorgan. Comparison of the remainder of the Hettangian is difficult in the absence of any horizons which can be correlated with certainty in both areas. In Trueman's paper, the lower boundary of the *angulata* zone is placed lower than in the zonal interpretation used in the present paper. Trueman (1920, p. 99) draws it at the first record of *Schlotheimia*, but three out of four species of that genus cited from the lowest part of the zone (*S. acuticosta* (Strickland), *S. aequalis* (Simpson), *S. gallica* S. S. Buckman; *loc. cit.*, p. 10) should be referred to *Waehneroceras*, rather than to *Schlotheimia* s.s., and if *Psilophyllites* is taken as marking the top of the *planorbis* zone, then the base of the *angulata* zone should be taken at about bed 65 of Trueman's sequence. *Alsatites* cf. *laqueolus* (Schloenbach), a *laqueus* subzone fossil, occurs about 20 ft. higher in bed 70.

If the *planorbis* zone is thus extended, about 70 ft. of beds in Glamorgan are represented by a maximum of 25 ft. in the neighbourhood of Keynsham.

The *angulata* zone is about 80 ft. thick (Trueman, 1922, p. 252, beds *aiii* and *aiv*; bed *aii* contains *Waehneroceras* and *Psilophyllites*, to judge from the species cited lower down the page), compared with 19 ft. at Saltford Cutting. Little palaeontological detail is available, but the appearance of 'large smooth ammonites (*S.* cf. *greenoughi*)' a few feet below the top of the zone (*op. cit.*, p. 265) recalls conditions at Keynsham.

The thickness of the *bucklandi* zone in Glamorgan is impressive. It affords an indication of the amount of condensation of the sequence which has occurred in Somerset in this zone. The upper limit of the zone is ill-defined, but the two lower subzones, *conybeari* and *rotiforme*, have a combined thickness of 108 ft., in contrast to a maximum of 5–6 ft. at Keynsham (Trueman, 1930, p. 149). *Metophioceras* ranges through about 34 ft. of strata, both large and small species being recorded. In the *rotiforme* subzone is found a sequence of faunas similar to that from Keynsham; *C. rotiforme* (J. de C. Sow.) and allied species in the lower part, and species of the *C. hyatti* group (recorded by Trueman as *Arnioceratoides* spp.; see Donovan, 1952, p. 736) in the upper part. *Charmasseiceras*, found already at the top of the *angulata* subzone at Keynsham, occurs only in the *rotiforme* subzone in South Wales, and *Vermiceras* has not been recorded at all.

The *bucklandi* subzone of South Wales is not known in sufficient detail for comparison, and there are hardly any definite records of ammonites. The large ammonites, 'too slender for *Paracoroniceras* or for *Coroniceras* of the *C. bucklandi* type' which Trueman found near the top of his section (1930, p. 155) could be *Coroniceras* (*Primarietites*) of the late *C.* (*P.*) *reynesi* group which mark the succeeding *gmuendense* subzone around Keynsham. Apart from this possibility, neither the *gmuendense* subzone nor any later horizons in the *semicostatum* are proved in Glamorgan.

## 7. THE AMMONITE SUCCESSION

The zones and subzones of the Lias proposed by Spath (1942) are used by the writer. Study of the succession in Somerset and elsewhere shows that some of Spath's subzones can be further subdivided, so that at least sixteen ammonite horizons can be recognised in the Blue Lias. It is not proposed, at present, to increase the number of subzones, although this might be justifiable after a study of broader scope than that described in this paper.

The ammonite horizons recognised are shown in the table opposite. The *planorbis* subzone cannot be subdivided satisfactorily in southern

## Ammonite faunas in the Keynsham area

| STAGES | ZONES | SUBZONES | AMMONITE FAUNAS | | HORIZONS PROVED AT LYME REGIS | REMARKS |
|---|---|---|---|---|---|---|
| SINEMURIAN | *semicostatum* | *sauzeanum* | *Euagassiceras spinaries* | ▲ | x | |
| | | *scipionianum* | *Agassiceras scipionianum,*<br>*Arnioceras acuticarinatum* | | ? | *scipionianum* Bed at Keynsham |
| | | *gmuendense* | *Paracoroniceras* spp.<br>*Coroniceras* (*Primarietites*) *reynesi* abundant | Range of *Arnioceras* | x | |
| | *bucklandi* | *bucklandi* | *Megarietites meridionalis*<br>*Arietites* spp. | | | |
| | | *rotiforme* | *Coroniceras* (*Primarietites*) *caprotinum, C.* (*P.*) *hyatti*<br>*C.* (*P.*) *rotiforme* | Range of *Vermiceras* | x<br>x | *Vermiceras* is not recorded from Lyme Regis<br>*Charmasseiceras* is recorded only from *bucklandi* and ? higher subzones at Lyme Regis |
| | | *conybeari* | *Coroniceras* (*Metophioceras*) spp. | Range of *Charmasseiceras* | x | |
| HETTANGIAN | *angulata* | *angulata* | (giant Schlotheimids)<br>*Schlotheimia* (*Schlotheimia*) *similis* | | x | |
| | | *laqueus* | *Alsatites liasicus, Laqueoceras* spp. | | x | *Alsatites* is known from Lyme Regis area (Spath, 1924, p. 202) but has not been found *in situ* on the coast |
| | *planorbis* | *johnstoni* | *Schlotheimia* (*Waehneroceras*) spp.<br>*Psiloceras* (*Caloceras*) *johnstoni* | | x<br>x | *Psilophyllites* associated with *Waehneroceras* at Lyme Regis |
| | | *planorbis* | *Psiloceras* (*Psiloceras*) *plicatulum*<br>*Psiloceras* spp. (smooth) | | x | *Psiloceras* Bed at Keynsham |

England (see also Donovan, 1952, p. 635). The *johnstoni* subzone, however, consists of two parts: a lower one with *Caloceras johnstoni* (J. de C. Sow.) and an upper one which lacks this species but is characterised by several species of *Waehneroceras*. This subdivision holds for Lyme Regis, north Somerset and South Wales. In Dorset and South Wales only, at the top of the beds with *Waehneroceras*, is found *Psilophyllites*, but it is not clear as to whether or not this genus marks a constant horizon.

At Saltford Cutting, *Laqueoceras* occurs below *Alsatites*, but these records are based on one or two specimens only, and either or both genera may have a greater range. At Farmborough, *Alsatites* appears first, but here again the evidence is inadequate to establish the ranges of the two genera.

The lower part of the *angulata* subzone is characterised by the slender-whorled *Schlotheimia similis* Spath, while the upper part is characterised by stouter-whorled species at both Lyme Regis and Bristol, but further palaeontological study of suitable material is necessary before a satisfactory subdivision of the subzone can be made. The *conybeari* subzone is condensed, but the thicker developments at Lyme Regis and in Glamorgan do not show any clear differentiation. The *rotiforme* subzone, on the other hand, shows a consistent sequence in the south of England, with ammonites of the group of *Coroniceras* (*Primarietites*) *rotiforme* below, and species with different inner whorls, such as *C.* (*P.*) *hyatti* Donovan and *C.* (*P.*) *caprotinum* (d'Orb.), above (*Arnioceratoides* [*recte Coroniceras s.s.*], recorded from the top of the subzone at Lyme Regis and Glamorgan, is probably the young of the same, or of related, species).

Little is known about the detailed stratigraphy of the *bucklandi* and *gmuendense* subzones at Keynsham, and even less about this at Lyme Regis and in South Wales. At Keynsham and Saltford, *Megarietites* appears after *Arietites*, and *Paracoroniceras* later than the abundant *Coroniceras* (*Primarietites*) *reynesi* Spath, but all these ammonites except the last are too rare to support any generalisation as to their true stratigraphic distribution.

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# The Carboniferous Basement Series of the Cross Fell Area, Cumberland and Westmorland

by J. G. CAPEWELL

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**ABSTRACT:** The field occurrence and petrography of the several hundred feet of Basement Series below the Melmerby Scar Limestone of Cross Fell and Cumrew are described. From the data obtained it is inferred that these rocks were derived from an upland area to the west, composed of Skiddaw Slates and Borrowdale Volcanic rocks and that they were laid down in an environment transitional between a continental flood plain in the north-west part of the outcrop and an unstable marine shelf in the south-east. The Roman Fell Beds, *sensu stricto*, are shown to be composed largely of desert-derived sand, and are to be correlated with the Red Sandstones of the Birk Beck Valley, not with the Cross Fell Basement Series.

## 1. INTRODUCTION

THE CARBONIFEROUS LIMESTONE Series of the Alston Block is underlain by several hundred feet of sandstones and conglomerates which outcrop in Teesdale (Harry, 1950), and more especially along the western escarpment near Cross Fell. This feature is mainly produced by the Melmerby Scar Limestone, the lowest and thickest of the Carboniferous Limestone sequence, and the underlying Basement Series are obscured by talus from this limestone along much of their outcrop.

Besides the Basement Series of undoubted Carboniferous age, in the Cross Fell area there occur also sporadic outcrops of conglomerates of a different type, usually known as the 'Polygenetic Conglomerate'. Probably these are older than the Basement Series but are not described in the present paper.

The term 'Basement Beds' has become well-established for the thick succession of non-calcareous rocks underlying the Melmerby Scar Limestone northwards from the Swindale Beck (Hilton) Fault (Turner, 1927, p. 341; Shotton, 1935, p. 645), although the usage is not that of officers of the Geological Survey who, in mapping the Cross Fell area, restricted the term to the rocks now known as the 'Polygenetic Conglomerate'. However, Goodchild (1874, p. 398) applied the term 'Roman Fell Beds' to include all the beds younger than the Silurian, yet underlying the Melmerby Scar Limestone. The latter term is now used in a far more restricted sense, embracing only the rocks capping Roman Fell, which show certain features contrasting with those of the Basement Series, farther north, as are described at the end of this paper.

As has been shown clearly by Garwood (1912) and Turner (1927), the Swindale Beck Fault forms an important tectonic line controlling Lower Carboniferous sedimentation, for, whereas the lowest recognisable horizon to the north is that of *Lithostrotion minus*, to the south rocks of *Cleiothyridina glabistria* age are developed, and each group has 'Basement Beds' below. The Basement Beds of the two areas are thus not equivalent. No work, however, has been possible south-east of Roman Fell, since this area is used as an artillery range and no comparison of the two developments of the Basement Beds has been attempted therefore.

This account, then, is virtually restricted to the beds underlying the Melmerby Scar Limestone from Swindale Beck as far north as they can be traced along the escarpment. Outliers at Cumrew, and west of the escarpment, are also described. The beds form a distinctive formation, several hundred feet in thickness, yet little studied hitherto on account of their lack of fossils. Since the term 'Basement Beds' includes rocks of widely differing ages, it is proposed that the strata described here be referred to as the 'Cross Fell Basement Series'. The Roman Fell Beds, *sensu stricto*, are distinct, and are described separately.

This work, forming part of a wider study, has been made possible by a grant from the Central Research Fund of the University of London for which the author wishes to make grateful acknowledgment.

## 2. FIELD EVIDENCE

(a) **Main outcrop.** In the north-western part of the outcrop a division of the Basement Series into a lower conglomeratic group and an upper sandstone group can be readily mapped, but south-east of Great Rundale these subdivisions cannot be recognised.

The most complete sections in the Basement Series are those in Grey Mare's Tail (grid ref. 625401) and in Ousbydale (650366). In the former the series totals at least 900 ft., the lowest beds being cut out by strike faulting. The beds dip upstream (i.e. ENE.) at 70°–90°, decreasing to 40° only at the extreme top. The first 300 ft. are referred to the Lower Group, and mainly

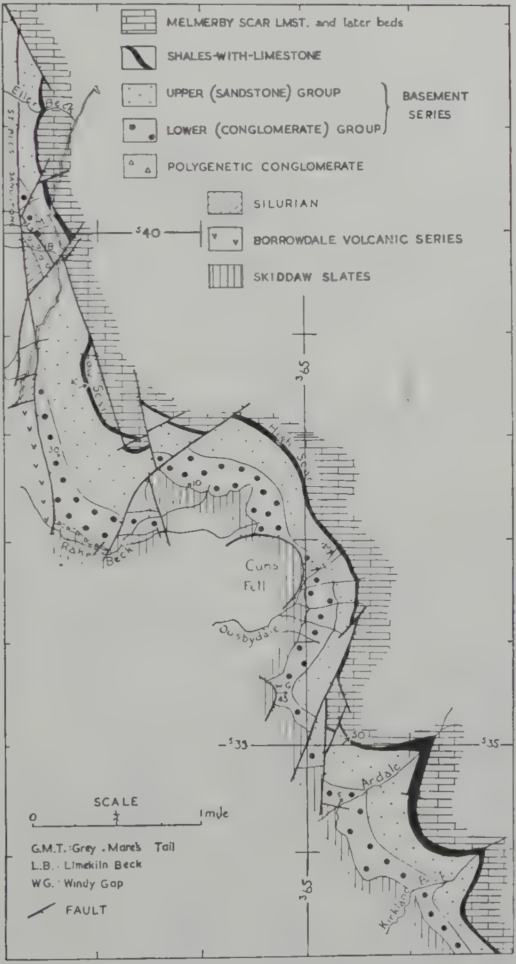

Fig. 1. Map of the Cross Fell Basement Series (north-western section), based on map by Shotton (1935), with modifications

consist of quartz-rich pebble-conglomerates, with subordinate pebbly sandstones and coarse calcareous sandstones, all of a purplish-red colour. The higher part of the section comprises a sequence of sandstones and subordinate flaggy siltstones, the harder beds giving rise to a series of small waterfalls. These rocks are purple in the lower part, passing up by alternation into entirely grey-green beds. The highest bed seen, a few yards below the main road, is a fine-grained grey calcareous sandstone. A gap follows before the shales-with-limestone[1] which underlie the Melmerby Scar Limestone are seen in Sailrigg Quarry.

In the most northerly streams in Ousbydale, the Lower Group rests on Skiddaw Slates at about 1200 ft. O.D., and consists of some 400 ft. of pebble-conglomerates, with minor flaggy sandstone bands and one marked band of red siltstone, about 250 ft. from the base, which is sufficiently impermeable to throw out a line of seepages. The Upper Group is dominantly arenaceous, with a suggestion of rhythmic sedimentation of (i) siltstone, (ii) current-bedded, often flaggy, sandstone, and (iii) fine pebble-conglomerate, or pebbly sandstone. Purple colours are dominant, but the highest one hundred feet of the formation again shows a passage into green beds. Other exposures of note in this part are to be seen in Rake Beck and Swire Sike (635373), below Melmerby Scar, but require no separate description.

Rhythmic bedding is seen again in Eller Gill (624412), north of Grey Mare's Tail, where alternations of siltstones, pebbly sandstones and conglomerates, followed by grey beds, are exposed. Only about 200 ft. of beds below the limestone appear to be present, but they are folded sharply, and probably there is also some hidden strike faulting.

Southwards from Ousbydale the conglomerates are well seen on Windy Gap (647355), in Ardale Beck (653344), Kirkland Beck (661336), Crowdundale Beck (683322) and Middle Tongue Gill (687318). In this area compression joints, passing through matrix and pebbles alike, are a conspicuous feature. In Kirkland Beck, the conglomerates show a significant close packing, with little matrix.

In the country south of Middle Tongue Beck, the lowest beds are usually faulted out, except in the deeper valleys which have cut down to the Skiddaw Slates on the east side of the fault. The most complete section in the central part of the outcrop is that in Sink Beck (696290), where 200 ft. of pebble-conglomerates are succeeded by beds of the Upper Group, flaggy at the base, but consisting mainly of massive quartzose sandstone, with dark shales appearing towards the top. In this section no red or purple beds are present, the dominant colour being pale—usually a buff tint.

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[1] These rocks form a transitional group between the Basement Series and the Melmerby Scar Limestone, but as they are marine, with an S2 fauna, they are better grouped with the latter (see Turner, 1927, p. 344).

In Great Rundale, crags of vertical pebble-conglomerate are present on Brownber (707274), but southwards it becomes impossible to recognise the two divisions. High Cup Gill is virtually devoid of exposures of Basement Series, though a recent slide has bared a 28-ft. section at about 1300 ft. O.D., on the northern side (733252). This shows rapid alternations of green sandy shales, flaggy sandstone and pebble-conglomerate, but no rhythm can be perceived. This exposure lies near the top of the series, a

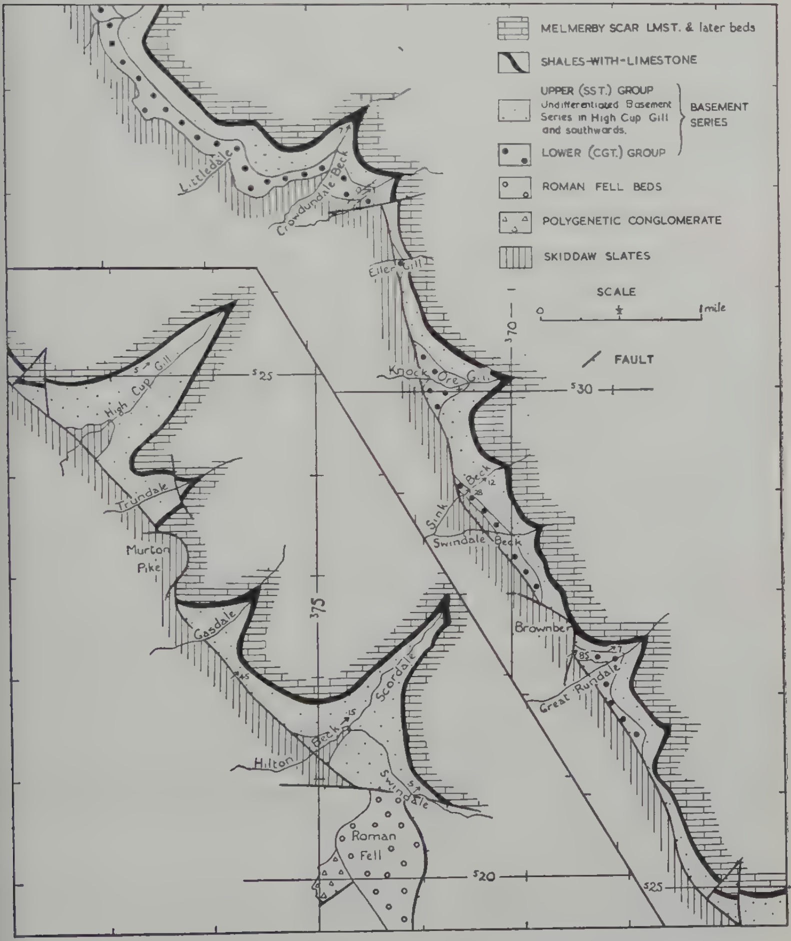


Fig. 2. Map of the Cross Fell Basement Series (south-eastern section), based on map by J. S. Turner (1927) and Shotton (1935), with modifications

little above a grey siliceous sandstone which makes a conspicuous feature on the valley sides hereabouts. The rock is best seen *in situ* under Delfekirk Scar (742220), but its residual blocks are abundant.

The Basement Series in Scordale and Swindale has been described by Turner (1927, p. 341). They consist of greenish shales, current-bedded sandstones and pebble-conglomerates, the last being found at all horizons. At the top of Lowfield Hush (752217) is exposed the passage into the overlying shale-with-limestone under the Melmerby Scar Limestone. About 25 ft. of massive sandstone, with thin conglomeratic bands, passes up into gritty limestone. A little higher a sandy dolomite is seen, followed by the Bryozoa Bed. Scordale is otherwise poor in exposures of the Basement Series, owing to widespread slipping, and mining activity. Swindale yields better exposures and it was from here that Shotton (1935, p. 645) records *Rhizodus hibberti*, a marine Carboniferous fish. The Swindale Beck Fault crosses about half a mile up the valley (see earlier, p. 214).

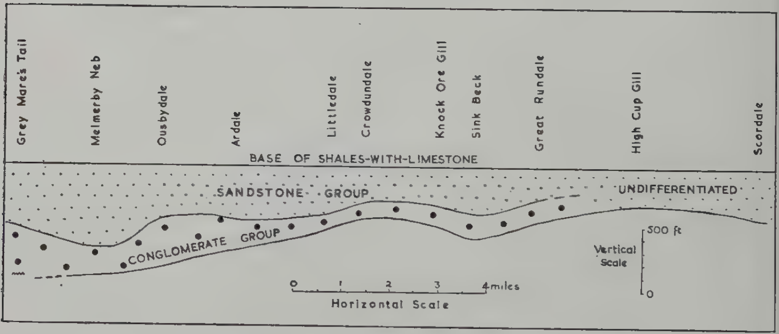


Fig. 3. Diagram showing lateral variation along the main outcrop of the Cross Fell Basement Series

(b) **Outliers west of the escarpment.** In the highly disturbed country west of the Pennine escarpment, Carboniferous strata are preserved occasionally in a greatly faulted belt extending from Melmerby to Howgill Castle (Shotton, 1935, p. 662). In this belt Cross Fell Basement Series are exposed: (i) in Ardale Beck and Acorn Sike (640341), (ii) in Kirkland Beck (653328), and (iii) in Crowdundale Beck (663313). Rocks seen near Howgill Castle (665293) may also belong to this formation.

In Ardale Beck, about 250 ft. of pebble-conglomerates, overlain by 100 ft. of current-bedded flaggy purple sandstone, are present, though not exposed continuously. The outcrop is faulted against Yoredale rocks, both upstream and downstream. Acorn Sike shows about the same thickness of conglomerate, but no sandstones are seen. Here the Basement Series are closely comparable with those seen about a mile distant, farther up Ardale.

Kirkland Beck reveals a succession of purple sandstones, the lower part being pebbly, and siltstones, exposed at intervals for about 300 yds. The total thickness of beds for which there is definite evidence is only 130 ft.

Crowdundale Beck, north of High Slack, yields exposures of purple and white sandstones, shales and pebble-conglomerates, apparently underlying a dolomitic limestone, which occur at intervals over a distance of 350 yds., but as there is much minor faulting and variation of dip, no thicknesses can be estimated.

(c) **Cumrew.** As a result of strike faulting, the Basement Series is cut out at the surface north of Gamblesby, and does not reappear for seven miles, i.e. until Cumrew is reached. Just east of this village, a sharp fold brings up the beds below the Melmerby Scar Limestone in a small outcrop about one and a half miles long and half a mile broad. The rocks have been described in the Brampton Memoir (Trotter & Hollingworth, 1932, pp. 20–2). In consequence, the following notes are supplementary to, or in modification of, this earlier work.

Underlying the Melmerby Scar Limestone, and usually grouped with it, are about 300 ft. of grey shales, poorly-exposed in Trowslinn Gill (558510), which are followed downwards by pebbly sandstones and red mudstones of the Basement Series. Further soft sandstones and mudstones are seen at intervals downstream. To the south of Trowslinn Gill, a prominent feature is made by a green current-bedded sandstone, exposed near Dunwalloght Castle (560502). In crags north of the gill, buff sandstone, underlain by pebble-conglomerates, is seen, and probably this horizon also forms the steep scarp 350 yds. west of the crags. At the northern end of this scarp are small cliffs showing at least 20 ft. of pebble-conglomerates, noteworthy for the well-rounded nature of most of the pebbles and for the scantiness of the matrix—features suggestive of the higher part of a beach.

The shift in the escarpment is due to a NE.–SW. fault, joining an ESE.–WNW. fault which terminates the scarp northwards (see Fig. 4). East of Turnberry (553519), a strong feature is again prominent, but probably is modified by glacial lateral drainage.

The thickness of Basement Series present at Cumrew, along an east–west line near Trowslinn Gill, appears to be of the order of 1000 ft. The anticlinal structure described by the Geological Survey, is not apparent in this part of the outcrop.

## 3. PETROGRAPHY

(a) **General.** A wide variety of detrital rocks is present in the Cross Fell Basement Series. The conglomerates show fairly constant features and are composed, essentially, of stable rock types. The sandstones vary from a

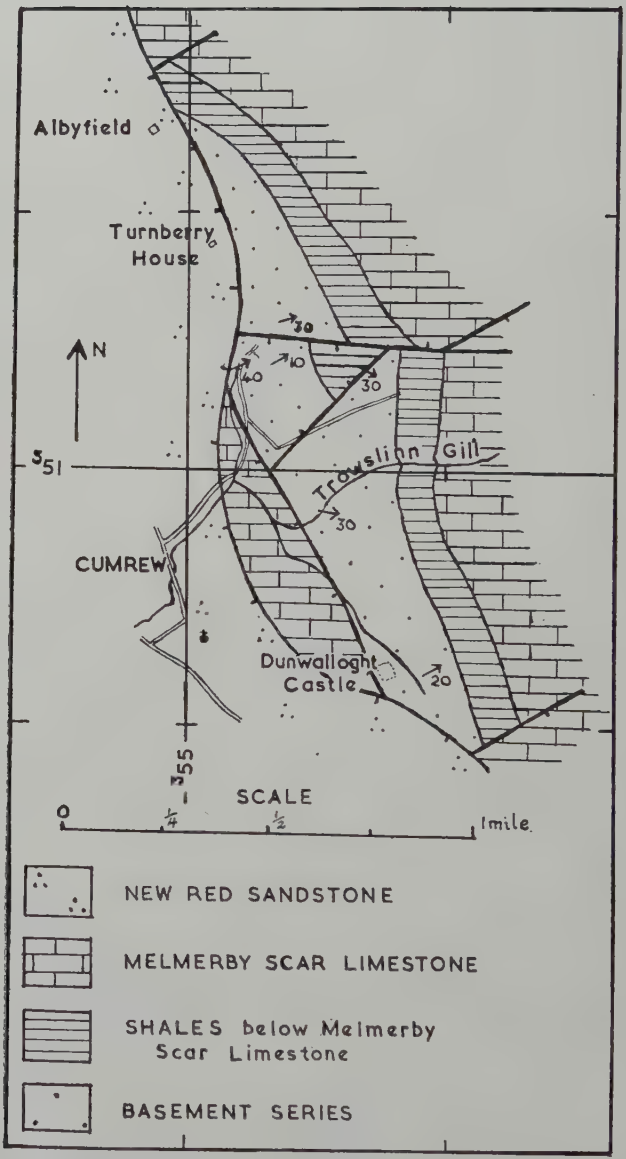


Fig. 4. Geological map of Cumrew, with drift omitted

calcareous purple type, often made up of slate grains, in the north-western part of the Series, to the buff quartzose one typical of the south-eastern part of the Series. Siltstones, both calcareous and non-calcareous, are common, and true shales come in towards the south-east.

(b) **Pebbles.** The rudaceous horizons in the Basement Series are quartz-conglomerates in the main, but other stable rock types are not uncommon as pebbles. For example, at Windy Gap (647355), a count showed that only two-thirds of the pebbles are of quartz or quartzite. The other types comprise mainly volcanic rocks, usually acid and silicified; rocks of greywacke type, chert and mica-lamprophyre.

Usually the igneous rocks can be matched with those found locally, either in the Borrowdale Series or in the post-Ordovician intrusions (see Hudson, 1936). The greywackes are much richer in chlorite than those of the Silurian of north-west England and probably are derived from coarser horizons in the Skiddaw Slates; some of the quartzites found as pebbles closely resemble the 'grits' of that formation. From Eller Gill (690312) a pebble of quartz-epidote rock was found which shows an irregular mosaic of subhedral grains of the two minerals, the epidote revealing a rough parallelism in terms of its optics.

The pebble suite of the conglomerates in the Cumrew area closely resembles that of the main outcrop and there is little to suggest that it is derived from any parent rocks other than the Borrowdale Volcanics and the Skiddaw Slates.

(c) **Sandstones.** Thin sections of several of the sandstones of Grey Mare's Tail (625401) have been studied because this locality gives a nearly complete section through the Basement Series of the north-western part. The thick dark greyish-purple sandstone near the base of the Upper Group consists dominantly of elongated, usually rounded, grains of slates and siltstones, together with angular and subangular quartz (Plate 7 A). Most of the slate grains are chloritic, but many were hematite-impregnated before sedimentation and also many have a pellicle of hematite; detrital pellets of this mineral are also not infrequent. The secondary cement of this rock is a mosaic of clear calcite showing well-developed polysynthetic twinning. Obviously the general colour of the rock is due to the mixture of the green chlorite with reddish hematite, the latter predominating.

The harder bands of purple sandstone in the middle of the group are well-sorted aggregates of fine sand, almost entirely quartz, with a cement of pellicular iron oxide and some secondary quartz. Occasionally detrital chlorite is seen.

The green sandstones near the top of the series are poor in iron oxide, except for sporadic limonite probably derived from pyrite. In one, the cement appears to be a fine mixture of chlorite and illite ('sericite'), probably derived from entrapped clay, though calcite also has infilled voids. This sandstone is essentially quartzose, with subangular and well-sorted constituent grains. The highest sandstone seen is similar to this rock, but has an abundant cement of calcite. A rock at a lower horizon shows much allogenic matter other than quartz, consisting of fine sediments of greywacke-type and devitrified lava. Again the cement is a chlorite-illite mixture, with patches of clear calcite.

The sandstones of the north-western part of the outcrop are well-sorted, as a rule, but never show any evidence of grain-rounding by wind abrasion.

Farther south-east, as already noted, the purple colours give place to pale buffs and greens. Some of the sandstones are quartzitic, as in the case of one which makes a conspicuous feature from Great Rundale southwards. The cement of these rocks is quartz in optical continuity. Well-rounded quartz grains are rarely seen, though generally the rounding is better than that seen in the Grey Mare's Tail sandstone. The volume of a pale grey-green sandstone from Swindale (757212) is only about two-thirds quartz, the remaining detrital grains being of a chlorite-sericite rock; the cement is secondary silica.

Generally the sandstones of Cumrew are petrographically similar to those of the main outcrop, again showing no evidence of wind-rounded grains. Red and green rocks are interbedded, indicating continually changing conditions.

(d) **Heavy Minerals.** The finer sandstones of the Basement Series, especially in the higher part, usually yield a large number of heavy minerals, though the suite is restricted, being virtually zircon, tourmaline, rutile and iron ores (see Table I).

Zircon shows evidence of more than one source, for three types of grain can be distinguished: (i) rounded, sometimes frosted; (ii) slightly-worn, clear; and (iii) sharp unworn. A division into colourless, dusky (by reason of inclusions), and purple has also been made, but there is little correlation between colour and form, except that the purple zircons are usually well-rounded.

Tourmaline usually occurs in well-worn grains of various colours, the commonest being pinkish-green. Generally it is subordinate in amount to zircon, except at Swindale (Hilton).

Rutile is a characteristic mineral of the suite, usually occurring as the bright brownish-red variety, though the clear amber-coloured type is not rare. The thicker red grains are noticeably pleochroic. Most of the deeply-coloured grains are fractured and angular in outline, the paler grains usually showing a more perfect crystal form. Pale yellow allogenic anatase has been noted at one place.

Epidote, in irregular yellowish-green pleochroic grains, is occasionally present, as is to be expected, since epidote-bearing pebbles have been found in the conglomerates.

TABLE I: **Percentages of non-opaque Heavy Minerals**

|  | Locality | ZIRCON |  |  |  | TOURMALINE |  |  |  |  |  | GARNET | RUTILE | EPIDOTE | HYPERSTHENE | MONAZITE | ANATASE | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Clear | Dusky | Purple | Total | Green | Blue | Brown | Parti-coloured | Dusky | Total |  |  |  |  |  |  |  |
| 1. | Cumrew | 42 | 16 | – | 58 | 18 | 2 | 6 | 2 | 2 | 30 | 4 | 8 | – | – | – | – | Abundant LEUCOXENE |
| 2. | Eller Beck | 18 | 10 | 8 | 36 | 36 | – | 20 | – | – | 56 | 2 | 2 | 4 | – | – | – | Abundant MUSCOVITE |
| 3. | Crowdundale Beck | 52 | 15 | P | 67 | 4 | – | 2 | – | – | 6 | – | 25 | – | – | – | P |  |
| 4. | Swindale Beck (Knock) | 61 | 10 | 12 | 84 | 10 | – | P | P | 1 | 12 | 1 | 3 | P | P | – | – |  |
| 5. | Brownber | 50 | 6 | 2 | 58 | 16 | 6 | 3 | 1 | 2 | 29 | – | 13 | P | – | P | – |  |
| 6. | High Cup Gill | 44 | 35 | 6 | 85 | 6 | – | 3 | – | – | 9 | – | 6 | – | – | – | – |  |
| 7. | Swindale Beck (Hilton) | 18 | 10 | 6 | 35 | 38 | 4 | 6 | 2 | 7 | 57 | P | 7 | – | P | P | – |  |
| 8. | Roman Fell | Approx. 60 |  |  |  | Approx. 40 |  |  |  |  |  | – | – | – | – | – | – | Flood of LEUCOXENE |

P = mineral present < 1%.

Garnet is of little importance. A mineral in ragged grains, with pelochroism pink to green, has been referred to hypersthene, and monazite also is occasionally present, in the form of yellow faintly-pleochroic ovoid grains giving a biaxial interference figure.

Opaque grains, mainly ilmenite-leucoxene, everywhere greatly outnumber grains of the non-opaque minerals.

## 4. PROVENANCE AND CONDITIONS OF DEPOSITION

In considering the probable derivation, and conditions of deposition, of the Cross Fell Basement Series, the following pieces of evidence are relevant:

(i) There is a general thinning of the series along the outcrop from north-west to south-west (from more than 900 ft. at Grey Mare's Tail to 400 ft. at Scordale).

(ii) A thinning of the series also takes place under the Alston Block. In Upper Teesdale, at Cronkley Scar, 140 ft. of Basement Carboniferous is recorded (Dunham, 1948, p. 13). In the Roddymoor boring in Co. Durham, Woolacott (1923, p. 59) ascribes a thickness of 82 ft. to the series, but this thickness consists partly of interdigitating marine beds, only 30 ft. being conglomerate or sandstone.[1]

(iii) The thick pebble-conglomerates of the Lower Group disappear south-east of Great Rundale. In the north-west, conglomerates are restricted to the lower beds, whereas in the south-east, thin conglomerates appear at all horizons.

(iv) Shales are absent in the north-west, the beds of finest grain being thin siltstones, but they are important in the south-east.

(v) Current-bedding of sandstones is frequently observed, and indicates shallow water conditions and a dominant current-flow from the west.

(vi) The dominant colour of the beds changes from purplish (modified by green detrital material) in the north-west, to green or buff in the south-east, indicating a concomitant change in environment of deposition.

(vii) The conglomerate pebbles show evidence of moderate transportation, and are probably derived from the Skiddaw Slates, the Borrowdale Volcanic Series, and their intrusions.

(viii) Sandstones composed of slate grains are common in the north-west but rare in the south-east.

(ix) Aeolian rounding of sand grains is absent; the abrasion is aqueous and rounding tends to increase towards the south-east.

(x) The heavy accessory minerals—zircon, tourmaline, rutile and leucoxene—are, on the whole, suggestive of a derivation from pre-existing sediments, though some undoubtedly first-cycle grains do occur.

---

[1] The marine beds are fossiliferous, but do not yield any forms of zonal significance (Lee, 1924, p. 146).

These facts all point to the sediments having been derived from an area of Skiddaw Slates and Borrowdale Volcanics lying to the west or north-west. The Carboniferous fish, *Rhizodus hibberti*, has been recorded from Swindale (Hilton), indicating marine conditions of deposition (Shotton, 1935, p. 643) for at least the rocks of the south-eastern part. Their pale colour would thus not be unexpected, the formation of hematite being unlikely under marine conditions. In the north-western part, however, the dominant purple colour, due to hematite round the allogenic minerals, is indicative of a non-marine environment—probably a low-lying flood plain in which periodic wetting and drying allowed oxidation of the iron and dehydration of the iron oxide to take place. In the Cumrew area probably the marine and non-marine environments alternated.

Therefore it is likely that, during the deposition of the series, a shore-line ran NNE.–SSW. approximately through the position of Cross Fell, the sediments to the west being fluviatile, while those to the east were laid down in a very shallow sea. The dividing line is not sharp, the two environments merging into each other. Only one rock has been diagnosed as a probable littoral deposit; a pebble-conglomerate, seen in Kirkland Beck, consisting of sub-rounded pebbles, mainly of quartz packed very closely together, with little matrix. The floor of deposition was probably fairly smooth, as indicated by Fig. 3, but there may have been irregularities, as noted by De Rance (1873).

Subsidence of the area probably went on as the sediments accumulated, but eventually marine conditions spread over the whole area. The highest beds in Grey Mare's Tail and Ousbydale become green before the unequivocally marine Shales-with-Limestone appear.

To the west, or north-west, of the present outcrop, then, a land area must be postulated, while southwards deep sea prevailed. The former must have had some relief at first, to allow the transportation of gravel, but was planed down as time went on. The line of the Swindale Beck Fault probably marks an earlier shore-line; presumably the northern boundary of the subsiding 'Ravenstonedale Gulf' of Tournaisian sedimentation. In the Shap-Ravenstonedale area, and to the south of Swindale Beck, *Lithostrotion minus* beds (equivalent to the Shales-with-Limestone) are underlain by the Ashfell Sandstone, and thus this bed is probably the marine continuation of the Cross Fell Basement Series. The Swindale Beck Fault, as has been shown by Shotton (1935, p. 674), is not continued by the Inner Pennine Fault in controlling Lower Carboniferous sedimentation. It runs away to the west-north-west, in the direction of the Eamont about Pooley Bridge. On the Carboniferous outcrop of the eastern side of the Lake District, Garwood (1912) mapped $C_1$ (*Cleiothyridina glabistria*) beds extending to the Eamont, with the Ashfell Sandstone above. North of the Eamont, the lowest zone definitely ascertained is that of *Lithostrotion* *minus* ($S_2$) (Earle, 1922, p. 525), though below this horizon, at Hutton John, for example, unfossiliferous dolomites underly a thin sandstone (probably the attenuated Ashfell Sandstone). In pre-$S_2$ times, then, the Eamont area was one of thin carbonate and sand deposition, probably lagoonal, and not one receiving thick detritus. The upland area supplying the Cross Fell sediments must thus have lain northward of this latitude.

A probable northward limit to the provenance can also be fixed, for in north-east Cumberland marine sedimentation also began much earlier than $S_2$-times. Probably at the time when the Cross Fell Basement Series were being laid down this area was sea, with limestone-shale deposition. At the surface the approximate southern margin of the basin is marked by the Stublick Faults, and their westward extensions in the Cote Hill district towards the Isle of Man (Trotter & Hollingworth, 1932, p. 17).

The evidence from Cumrew supports this conclusion. There the age and provenance of the rocks is similar to that of the rocks of the main outcrop, but the interdigitation of red and green beds indicates continually changing conditions of sedimentation. Six miles north of Cumrew, the Lower Limestone Group (of which the Melmerby Scar Limestone forms a part) is underlain by a great thickness of Lower Bernician and Tuedian beds, largely marine, and laid down in the Northumbrian trough of sedimentation (Trotter & Hollingworth, 1932). At Cumrew the unstable conditions near the edge of this trough are reflected in the variety of rock types and rock colours.

Thus the high ground supplying the detritus would have lain roughly in the country north of Penrith (now known as Inglewood Forest)—an area of Borrowdale Volcanics, and probably of Skiddaw Slates, now concealed by the Carboniferous and New Red Sandstone of the post-Triassic Vale of Eden syncline (see Fig. 5).

These inferences, it may be noted, would rule out the suggestion made by Trotter & Hollingworth (1928, p. 435) that early in Lower Carboniferous times a narrow marine strait joined the Ravenstonedale and Brampton areas of sedimentation. On the contrary, the Alston area and the Lake District probably formed a continuous massif, as suggested by Goodchild (1889, p. 271) many years ago.

## 5. THE ROMAN FELL BEDS

Immediately to the south of the Swindale Beck Fault lies the thrust mass of Roman Fell (Turner, 1927, p. 364; Shotton, 1935, p. 678). The highest part of the hill is composed of at least 400 ft. of purple-red current-bedded sandstone with scattered pebbles of quartz and occasional conglomeratic bands. Turner calls these rocks 'Roman Fell Beds' *sensu stricto*. He was impressed by the contrast between them and the Basement

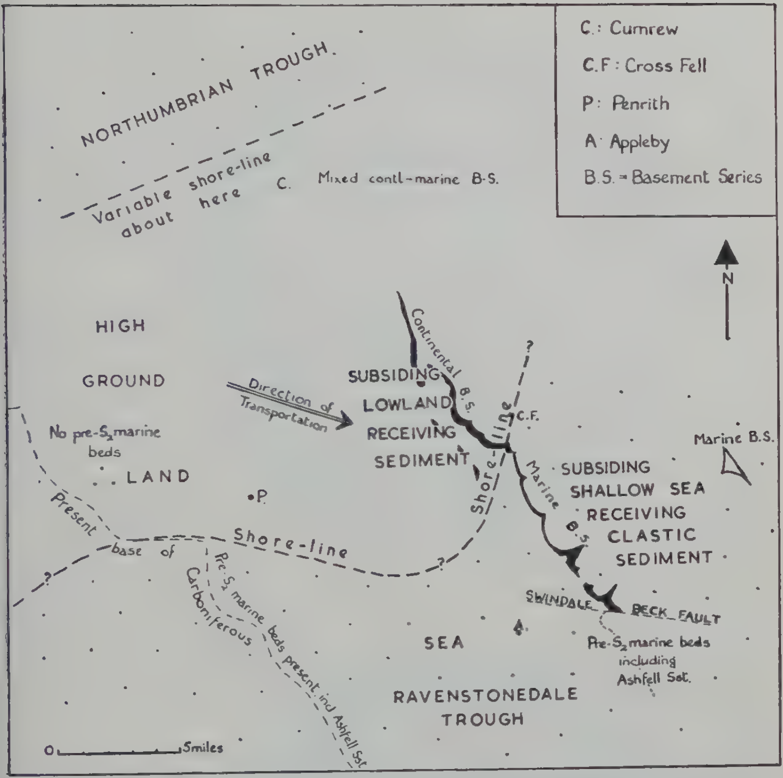


Fig. 5. Suggested palaeogeography during the time of the deposition of the Cross Fell Basement Series

Series of Swindale and Scordale and in consequence put forward the view that they are an older group of rocks, largely denuded prior to the deposition of the Carboniferous. He assigned to them a possible Devonian age (*loc. cit.*, p. 351).

Shotton, on the other hand, compares these Roman Fell Beds with the Basement Series as they are developed in the north-western part of the Cross Fell outcrop and, bearing in mind the degree of translation along the thrust, returns to Goodchild's view that the Roman Fell Beds (*s.s.*) and the Basement Series (as defined here) are one and the same formation (Shotton, 1935, p. 645).

Petrographically, however, the Roman Fell Beds contrast strongly with the Basement Series at localities north of the Swindale Beck Fault. Under the microscope the sandstones are seen to consist of well-rounded quartz grains with conspicuous pellicular hematite, the intergranular voids often being completely filled with secondary quartz grown in optical continuity with the original quartz (Plate 7, Fig. B). As a result of this latter feature, the rounded nature of the sand grains is not apparent in hand specimen. Sorting is good, but not perfect, with nearly all the grains falling within the limits 0.2–0.5 mm. (estimated from thin sections). The sandstones also have pebbles of quartz scattered through them, and there are occasional conglomeratic bands. In the lower beds which are seen in the scar to the west of Roman Fell summit, purple shale galls are numerous. Current-bedding is conspicuous but no dominant direction can be made out.

Thus the Roman Fell Beds must be interpreted as sub-aqueous deposits of desert-derived sands, probably laid down in a playa-like flood plain, the shale galls being the result of contemporaneous desiccation of newly deposited muds. No similar rocks occur in the Cross Fell area, but both lithologically and petrographically, there is a close resemblance to the Red Sandstone Group of the Birk Beck Valley (see Capewell, 1955). The stratigraphical evidence is negative, since the Roman Fell Beds are a thrust mass, having no succeeding beds, and they rest partly on Polygenetic Conglomerate, partly on various Ordovician horizons, and partly on a thrust-plane. The Birk Beck Red Sandstone rest partly on older Basement beds and partly on Silurian rocks. The thickness of the preserved Roman Fell Beds compares closely with that of the Red Sandstones. The respective outcrops are now some twelve miles apart, but, as Turner & Shotton have shown, Roman Fell is a mass thrust from the west, possibly for some miles, and the positions of the present outcrops were probably much closer before the thrusting took place.

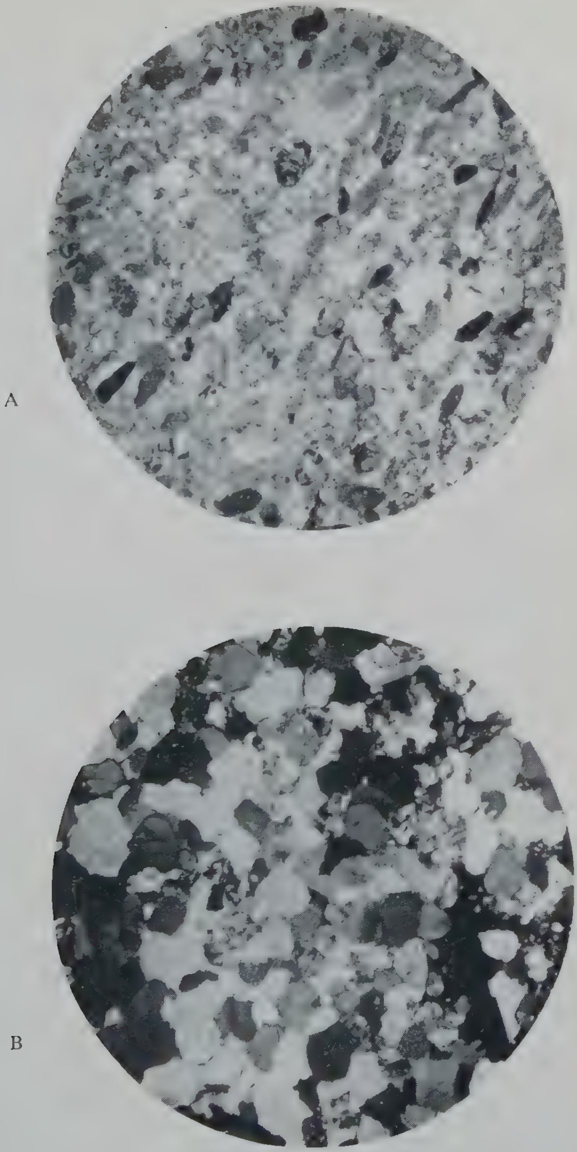
Thus it is suggested that the Roman Fell Beds are to be correlated with the Red Sandstone Group of the Birk Beck Valley, and hence are of pre-$C_1$-age, and not of pre-$S_2$-age as are the main Basement Series of Cross Fell.

## 6. SUMMARY OF CONCLUSIONS

1. The Cross Fell Basement Series (north of the Swindale Beck Fault) is regarded as of Carboniferous age, since marine $S_2$-beds overlie them conformably. Except in the south-east, the series may be divided into a Lower (Conglomerate) Group, and an Upper (Sandstone) Group, the variations in thickness, along the outcrop, being summarised in Fig. 3.

2. The conglomerates are composed mainly of quartz pebbles, but pebbles of volcanic rocks, lamprophyres, chert, quartzites and greywackes are also found.

3. The sandstones of the north-western part of the outcrop are purple rocks, often made up of slate grains. Frequently the cement is calcite. Wind-rounded grains are significantly absent.



[*To face p.* 228

4. The sandstones of the south-eastern part are essentially pale in colour, either buff or green, and are frequently quartzitic.

5. The heavy minerals are zircon, tourmaline, rutile and leucoxene, mostly well-worn; other species are insignificant.

6. The Basement Series were probably derived from an upland area to the west of the present outcrop—one made up of Skiddaw Slates and Borrowdale Volcanics and now underlying the Inglewood Forest area. The environment of deposition was continental, merging into a marine one towards the south-east. Rhythmic sedimentation is discernible occasionally.

7. The Basement Series of Cumrew are similar to, and correlated with, those of Cross Fell, but probably were laid down in a varying environment, alternately marine and continental.

8. The Roman Fell Beds (*sensu stricto*) are pebbly current-bedded sandstones composed of wind-rounded quartz grains with a quartzose cement grown in optical continuity with the original grains. Shale galls are common. They contrast strongly with rocks of the Cross Fell Basement Series, and it is suggested that they be correlated with the Red Sandstones of the Birk Beck Valley, with which they are closely comparable.

## EXPLANATION OF PLATE

(a) Photomicrograph of sandstone from Grey Mare's Tail, showing elongated grains of slate and a few angular grains of quartz in a cement of clear calcite. P.P.L. x 25.

(b) Photomicrograph of sandstone from summit of Roman Fell, showing rounded grains of quartz and chert, with pellicular hematite and cement of quartz in optical continuity with quartz grains. X.N. x 25.

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# Notes on the base of the Gault in Wiltshire

by R. CASEY[1]

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**ABSTRACT:** On palaeontological grounds the ferruginous basement-beds of the Gault at Dinton, Vale of Wardour, and near Dilton Marsh, North Wiltshire, are correlated with the bottom few feet of the Isle of Wight Carstone. They represent the basal part of the Albian zone of *Douvilleiceras mammillatum*, and are earlier than the base of the Gault at Okeford Fitzpaine, North Dorset.

IN ITS WESTERLY extension through Wiltshire the Gault oversteps the Lower Greensand and passes unconformably across various members of the Jurassic System. Owing to the paucity of exposures, and the lack of opportunity for fossil-collecting, it has not been possible hitherto to relate this transgression to the Albian time-scale established in other areas. It is important, therefore, to place on record information from two exposures in Wiltshire which have yielded material for precise age-determination of the basement-beds of the Gault. This material is preserved in the Geological Survey Museum, London, and I am indebted to the Director of H.M. Geological Survey for permission to examine it.

A well sunk north-east of the church at Dinton, Vale of Wardour, in 1890 gave the following (summarised) section:

| | | ft. | in. |
|---|---|---|---|
| *Gault clay* | | | |
| *Gault basement-beds* | Hard grey ferruginous sandy rock, fossils | 5 | 8 |
| | Reddish-brown sandstone with scattered pebbles, fossils and fragments of wood | 2 | 6 |
| | Layer of small pebbles ... ... ... | | 6 |
| *Lower Greensand* | | | |

This was recorded by Jukes-Browne in 1891 and a further description of the section, with lists of fossils from the different beds, was published in 1900 (Jukes-Browne, 1900, p. 228). Concerning the Gault in this section, Jukes-Browne commented: 'It will be noted that the basement-beds are here 8 ft. 8 in. thick and it might have been expected that they would yield the fauna of the zone of "*Ammonites mammillatus*", but this does not seem to be the case.' In the Salisbury Memoir, Clement Reid (1903, p. 32) again referred to the Dinton section and observed that 'its fossils belong to a

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higher zone than that of "*Ammonites* (*Acanthoceras*) *mammillatus*". Elsewhere in the same work (1903, p. 35) he assigned the Gault basement-beds of the Dinton well to the zone of '*Ammonites interruptus*' [*Hoplites dentatus*] and expressed the opinion that the *mammillatum* zone, known to be present at Okeford Fitzpaine, North Dorset, was probably represented in the sandstone below.

Re-examination of the fossils, in the light of improved knowledge of the faunal characters of the strata at the Lower Greensand–Gault junction, shows that the basement-beds of the Gault in the Dinton section are *earlier* than the maximum development of *Douvilleiceras mammillatum*, though still within the broad *mammillatum* zone. Fossils from the reddish-brown sandstone are identified as follows: *Sonneratia* sp. nov., *Grammatodon* (*Nanonavis*) *carinatus* (J. Sow.), *Inoceramus salomoni* d'Orb., *I.* sp. nov., *Pseudolimea* sp., *Modiolus* sp., *Cuneolus lanceolatus* (J. de C. Sow.), *Entolium orbiculare* (J. Sow.), *Pinna* sp., *Panope gurgitis* (Brongn.) var. *plicata* (J. de C. Sow.), *Pterotrigonia* sp., indet. venerid lamellibranch, ? *Gyrodes genti* (J. de C. Sow.), terebratulid brachiopods, including *Terebratula* cf. *capillata* d'Archiac, *Holaster* sp. From the grey sandy rock: *Sonneratia* sp., *Inoceramus* sp. nov., *Cucullaea glabra* Park., *Grammatodon* (*Nanonavis*) *carinatus* (J. Sow.), ? *Thetironia minor* (J. de C. Sow.), *Pholadomya fabrina* d'Orb., *Semisolarium* sp.

It emerges from a re-examination of the fossils that the ammonites, recorded by Jukes-Browne (1900, p. 228) as '*Ammonites* sp. (? *deshayesi* or *denarius*)' and as '*Ammonites* (*Hoplites*) sp.', are species of *Sonneratia*, a genus which in the south-east of England is confined to the *mammillatum* zone, it being the dominant ammonite genus in the basal part of that zone. The Dinton specimens cannot be referred to any described species, but, as mentioned below, conspecific or closely allied forms have been collected from the bottom few feet of the Isle of Wight Carstone, and from the lowest part of the *mammillatum* zone in the Weald.

The lamellibranch listed above as *Inoceramus* sp. nov. (*I.* sp., large, in Jukes-Browne, 1900, p. 228) has a wide distribution in south-east England, where it occurs only in the topmost *tardefurcata* zone and the immediately overlying portion of the *mammillatum* zone. The species has been recorded from the Carstone of the Isle of Wight as *Inoceramus* ? *neocomiensis* d'Orb. (Jackson, 1939, p. 76) and from the bottom of the *mammillatum* zone of Wrotham, Kent, as *I.* cf. *anglicus* Woods (Brown, 1941, p. 11). It is a forerunner of *I. salomoni* of the *mammillatum* zone, and the association of the two species at Dinton dates the containing beds as early *mammillatum* age as surely as do the ammonites. *Inoceramus salomoni* is presumably the species recorded by Jukes-Browne as *I. concentricus*.

A section close to the middle of the old working face of the Bremeridge pit, near Dilton Marsh, North Wiltshire, was examined by Mr. G. A.

Kellaway in 1943 and I have been permitted to quote the following description, summarised from his notes:

| | | ft. | in. |
|---|---|---|---|
| *Gault clay* (weathered) | (seen) | 5 | 6 |
| *Gault basement-beds* | Earthy and pebbly ironstone with septarian nodules and scattered limonitic ooliths, passing into | 3 | 0 |
| | Sandy and ferruginous clays, dark bluish-grey, with pebbles and lumps of clay. A layer of resorted clay with broken *Ostrea delta* at base | 2 | 6 |
| *Kimmeridge Clay* | | 12 | 0 |
| *Westbury Ironstone* | (seen) | 6 | 0 |

The sandy and ferruginous clay yielded *Sonneratia* spp., *Grammatodon* (*Nanonavis*) *carinatus* (J. Sow.), *Pholadomya fabrina* d'Orb., *Linotrigonia* (*Oistotrigonia*) cf. *archiaciana* (d'Orb.), *Pterotrigonia* sp., *Panope gurgitis* (Brongn.) var. *plicata* (J. de C. Sow.), '*Pecten*' cf. *cometus* d'Orb., and terebratulid and rhynchonellid brachiopods of undetermined genera and species. This faunal assemblage has much in common with that of Dinton, and the species of *Sonneratia*, although imperfectly preserved, are likewise considered to be of early *mammillatum* age. The nodules in the earthy and pebbly ironstone are remarkable for containing large *Ceriopora*-like bryozoans with anastomosing branches up to 30 mm. in diameter. From this bed Mr. Kellaway also obtained portions of a giant species of *Douvilleiceras*, comparable with that found in the top of the *tardefurcata* zone at Folkestone (Casey, 1950, pp. 271–2) and in the basal *mammillatum* zone of Westerham, Kent.

From the foregoing observations it is concluded that the ferruginous basement beds of the Gault at Dinton, and near Dilton Marsh, belong to the basal portion of the *mammillatum* zone. This horizon has its maximum development in the Carstone of the Isle of Wight, and at Dunnose, in particular, the bottom ten feet or so have yielded a rich *Sonneratia* fauna among which the Dinton and Bremeridge species can be placed. In terms of the Folkestone succession these beds lie on the same general horizon as the *Sonneratia kitchini* bed, near the top of the Folkestone Beds of the Lower Greensand (Casey, 1950, p. 270). In east Sussex this *Sonneratia* horizon is again in a Gault facies, and at Chalvington, as at Leighton Buzzard, Bedfordshire, it is part of a condensed deposit which also contains elements from the underlying *tardefurcata* zone of the Lower Albian (Casey, 1950, p. 284).

It is evident that a considerable interval of time elapsed before the Gault sea spread into the adjacent area of north Dorset, for several distinct faunal assemblages, such as that of the Main Mammillatum bed and the 'Sulphur Band' of Folkestone, existed between the period of deposition of the basal *mammillatum* zone and the subzone of *Douvilleiceras inaequinodum*, to which is referred the base of the Gault at Okeford Fitzpaine (Spath, 1925, p. 75).

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# The Gault at Greatness Lane, Sevenoaks, Kent

by R. A. MILBOURNE

Received 4 March 1954

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**ABSTRACT:** The lithological and faunal succession of the Gault at Greatness Lane, Sevenoaks, is described. The exposure gives a sequence from the middle of the *Hoplites dentatus* zone (Middle Albian) to the base of the *Mortoniceras inflatum* zone (Upper Albian). Compared with the Gault of Folkestone, the Greatness section shows an increase in thickness of the *Anahoplites intermedius* and *Dimorphoplites niobe* subzones of the *H. dentatus* zone, but an incomplete representation of the *Euhoplites lautus* zone.

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## 1. INTRODUCTION

IN RECENT YEARS a section in the Gault has been exposed at Greatness Lane, Sevenoaks, by the Sevenoaks Brick Works Limited. The pit lies three-quarters of a mile north-east of Sevenoaks (Bat and Ball) Railway Station, and about one third of a mile north of the Sevenoaks Brick Works Office Buildings. It provides a clear section of about 40 ft. of clay. The Gault has been worked in this neighbourhood for many years: for instance, an exposure at this locality was mentioned by Jukes-Browne (1900, p. 85). The present workings were visited by the Geologists' Association in 1949 (Austin Browne, 1949) and in 1954 (Milbourne, 1955); an outline of the succession has been given by M. F. Khan (1952, p. 74), who has studied the foraminiferal content of the clays, and the pit has been discussed by R. Casey (1954) in relation to the occurrence of the ammonite *Falciferella.* The present paper gives a fuller account of the succession and its palaeontological characters, and discusses the correlation with the standard Gault sequence at Folkestone. The succession is similar to that described by Wright (1946) at Dunton Green, one and a half miles to the west.

## 2. STRATIGRAPHICAL AND FAUNAL SUCCESSION

The pit shows both dip sections, and strike sections. It is situated in an area of tectonic disturbance, and the normal westerly dip of 5° in the working face suddenly increases to 40° west near the western extremity of the present exposure. The succession is as follows:

SECTION OF THE GAULT AT GREATNESS LANE, SEVENOAKS

| Bed | | ft. | in. |
|---|---|---|---|
| 35. | Light grey clay, to top of pit | 2 | 0 |
| 34. | Line of small white phosphatic nodules | | 1 |
| 33. | Light grey clay, with lenticles of 'Red Rock' | 1 | 8 |
| 32. | Line of small grey phosphatic nodules | | 1 |
| 31. | Light grey clay, with crushed fossils | 1 | 6 |
| 30. | Band of black phosphatic nodules, with many fossils | | 3 |
| 29. | Blue-grey clay | | 7 |
| 28. | Line of phosphatic nodules | | 1 |
| 27. | Blue-grey clay | | 9 |
| 26. | Line of small phosphatic nodules | | 1 |
| 25. | Blue-grey clay | | 5 |
| 24. | Line of phosphatic nodules | | 1 |
| 23. | Blue-grey clay | | 3 |
| 22. | Line of phosphatic nodules | | 1 |
| 21. | Blue-grey clay | | 10 |
| 20. | Line of phosphatic nodules | | 1 |
| 19. | Blue-grey clay | | 5 |
| 18. | Dense band of phosphatic nodules, with many fossils | | 4 |
| 17. | Blue-grey clay with orange streaks | 1 | 11 |
| 16. | Line of crushed fossils and some phosphatic nodules | | 1 |
| 15. | Grey clay, with orange mottling | 1 | 11 |
| 14. | Line of phosphatic nodules and crushed fossils | | 1 |
| 13. | Grey clay, with fawn and red mottling | 1 | 10 |
| 12. | Line of ironstained phosphatic nodules | | 2 |
| 11. | Fawn-grey clay | 6 | 3 |
| 10. | Band of crushed fossils | | 1 |
| 9. | Fawn-grey clay, with lenticles of hard 'Red Rock' at base | 2 | 6 |
| 8. | Line of brown and black phosphatic nodules | | 2 |
| 7. | Grey clay, with many crushed fossils | 2 | 4 |
| 6. | Line of black phosphatic nodules | | 2 |
| 5. | Dark grey clay, with crushed fossils | 4 | 6 |
| 4. | Line of phosphatised ammonite body chambers | | 2 |
| 3. | Dark grey clay, with many crushed fossils and chocolate-coloured nodules scattered throughout | 7 | 6 |
| 2. | Line of black phosphatic nodules, with many fossils | | 4 |
| 1. | Black unfossiliferous clay, seen for | 1 | 0 |
| | Total | 40 | 7 |

Fossils occur throughout all the beds in varying degrees of abundance and preservation. The following were collected *in situ*:

Bed 35. **Ammonoidea**—*Hysteroceras orbignyi* (Spath), *Beudanticeras beudanti* (Brongniart), *Euhoplites inornatus* Spath, *Hamites* spp. **Actinozoa**—*Trochocyathus conulus* (Phillips). **Echinodermata**—*Isocrinus fittoni* (Austen).

Bed 34. **Ammonoidea**—*Hysteroceras orbignyi*, *H. subbinum* Spath, *H.* aff. *varicosum* (J. de C. Sow.), *Anahoplites planus* (Mantell), *Epihoplites compressus* (Parona & Bonarelli), *Ep. trifidus* (Spath), *Euhoplites subcrenatus* Spath, *E. ochetonotus* (Seeley), *E. inornatus*. **Vertebrata**—teeth and vertebrae of fish. **Lamellibranchia**—*Inoceramus sulcatus Parkinson.*

Bed 33. **Lamellibranchia**—*Inoceramus sulcatus.*

Bed 32. **Ammonoidea**—*Anahoplites planus*, *Epihoplites compressus*, *Euhoplites subcrenatus*, *E. inornatus*, *E. sublautus* Spath, *E. armatus* Spath, *E. ochetonotus*, *Hysteroceras orbignyi*, *H.* aff. *simplicicosta* Spath, *Dimorphoplites chloris* Spath, *Hamites* spp. **Vertebrata**—fragments of reptilian bone. **Lamellibranchia**—*Pholadomya* sp.

Bed 31. **Lamellibranchia**—*Inoceramus sulcatus*, *Nucula pectinata* J. Sow. **Crustacea**—*Etyus martini* Mantell, *Notopocorystes stokesi* (Mantell).

Bed 30. **Ammonoidea**—*Dipoloceras cristatum* (Brongniart), *Anahoplites planus*, *Beudanticeras subparandieri* Spath, *B. beudanti*, *Dimorphoplites* cf. *silenus* Spath, *Epihoplites compressus*, *Euhoplites armatus*, *E. trapezoidalis* Spath, *E. sublautus*, *E. proboscideus* (J. Sow.), *E. subcrenatus*, *E. ochetonotus*, *Hysteroceras capricornu* Spath, *Hamites* spp. **Nautiloidea**—*Eutrephoceras* sp. **Lamellibranchia**—*Inoceramus sulcatus*, *Nucula pectinata*, *N. albensis* d'Orb., *Nuculana vibrayeana* (d'Orb.).

Bed 29. **Lamellibranchia**—*Inoceramus sulcatus.*

Bed 28. **Ammonoidea**—*Epihoplites compressus.* **Lamellibranchia**—*Inoceramus sulcatus.* **Vertebrata**—Dermal scutes of Crocodile.

Bed 26. **Ammonoidea**—*Dipoloceras cristatum*, *Epihoplites compressus*, *Euhoplites trapezoidalis*, *E. sublautus.* **Lamellibranchia**—*Inoceramus sulcatus.*

Bed 24. **Ammonoidea**—*Dipoloceras cristatum*, *Beudanticeras beudanti*, *Epihoplites compressus*, *Euhoplites ochetonotus*, *E. subcrenatus*, *E. sublautus*, *Hamites* sp. **Lamellibranchia**—*Inoceramus sulcatus.*

Bed 22. **Ammonoidea**—*Epihoplites compressus*, *Euhoplites inornatus*, *E. trapezoidalis.* **Lamellibranchia**—*Inoceramus sulcatus.*

Bed 20. **Ammonoidea**—*Dipoloceras* sp., *Epihoplites compressus*, *Euhoplites sublautus*, *E.* sp. nov., *Neophlycticeras jayetti* Breistroffer, *Hamites* spp. **Crustacea**—*Notopocorystes stokesi.* **Lamellibranchia**—*Inoceramus sulcatus.*

Bed 19. **Lamellibranchia**—*Inoceramus sulcatus.*

Bed 18. **Ammonoidea**—*Anahoplites planus*, *A. splendens* (J. Sow.), *A.* aff. *daviesi* Spath, *Beudanticeras subparandieri*, *B. beudanti*, *Dimorphoplites* aff. *doris* Spath, *D. glaber* Spath, *D. chloris*, *D.* cf. *silenus*, *D. tethydis* (Bayle), *D. biplicatus* (Mantell), *D.* aff. *pinax* Spath, *Dipoloceras cristatum*, *D. bouchardianum* (A. d'Orb.), *D. fredericksburgense* Gayle Scott, *D.* sp. nov., *Epihoplites compressus*, *Ep. trifidus*, *Euhoplites lautus* (J. Sow.), *E. lautus* var. *duntonensis* Spath, *E. trapezoidalis*, *E. bucklandi* Spath, *E.* aff. *truncatus* Spath, *E. proboscideus* (J. Sow.), *E. sublautus*, *E.* aff. *vulgaris* Spath, *E. subcrenatus*, *E. opalinus* Spath, *E. armatus*, *E. aspasia* Spath, *E. ochetonotus*, *E. subtuberculatus* Spath, *Hysteroceras* aff. *orbignyi*, *H.* aff. *symmetricum* (J. de C. Sow), *Hamites maximus* J. Sow., *Hamites* spp., *Pseudhelicoceras* sp., *Turrilitoides* (*Proturrilitoides*) *densi-*

*costatus* (Passendorfer). **Nautiloidea**—*Eutrephoceras* spp. **Lamellibranchia**—*Inoceramus concentricus* Parkinson, *I. sulcatus*, *Nucula pectinata*, *N. albensis*, *N. ovata* Mantell, *Nuculana vibrayeana*, *N. solea* d'Orb., '*Cardita*' *tenuicosta* (J. de C. Sow.). **Crustacea**—*Notopocorystes stokesi*, *Eucorystes broderipi* (Mantell), *Homarus longimanus* (J. Sow.), *Enoploclytia dixoni* (Bell). **Vertebrata**—Teeth of fish; jaw of a young Crocodile.

Bed 17. **Ammonoidea**—*Anahoplites planus*, *Dimorphoplites chloris*, *D.* cf. *doris*, *D. tethydis*, *D. biplicatus*, *Euhoplites lautus*, *E. bucklandi*. **Lamellibranchia**—*Inoceramus concentricus*. **Crustacea**—*Cretiscalpellum unguis* (J. Sow.).

Bed 16. **Ammonoidea**—*Anahoplites splendens*, *Dimorphoplites* aff. *pinax*, *D. glaber*, *D. chloris*, *D. tethydis*, *D. doris*, *Euhoplites lautus*, *Hamites gibbosus* J. Sow. **Lamellibranchia**—*Inoceramus concentricus*, *Nucula pectinata*, *N. albensis*, *Plicatula gurgitis* Pictet & Roux.

Bed 15. **Ammonoidea**—*Dimorphoplites doris*, *Anahoplites splendens*, *E. aspasia*, *E. loricatus* Spath (late mutation). **Echinodermata**—*Isocrinus fittoni*. **Vertebrata**—Teeth of *Squatina* sp.

Bed 14. **Ammonoidea**—*Anahoplites planus*, *A. splendens*, *Dimorphoplites doris*, *D. pinax*, *D. tethydis*, *Euhoplites truncatus*, *E.* aff. *nitidus* Spath, *Hamites* spp. **Lamellibranchia**—*Nucula pectinata*, *Inoceramus concentricus*, *Turnus* sp. in fossil wood.

Bed 13. **Crustacea**—*Notopocorystes stokesi*. **Lamellibranchia**—*Inoceramus concentricus*. Fossil wood.

Bed 12. **Ammonoidea**—*Anahoplites splendens*, *Dimorphoplites doris*, *D. chloris*, *D. aff. pinax*, *Euhoplites loricatus*, *E. aspasia*, *E. subtuberculatus*, Pathological Hoplitids.

Bed 11. **Ammonoidea**—*Dimorphoplites niobe* Spath, *Euhoplites subtuberculatus*, *E. pricei* Spath.

Bed 10. **Ammonoidea**—*Dimorphoplites niobe*, *Dipoloceras* (*Dipoloceroides*) *subdelaruei* (Spath), *Euhoplites subtuberculatus*, *E. aspasia*, *E. pricei*, *Hoplites* sp. nov., *Hamites* spp. **Lamellibranchia**—*Plicatula* sp., *Ostrea* sp., *Inoceramus concentricus*. **Echinodermata**—*Hemiaster bailyi* Forbes.

Bed 9. **Ammonoidea**—*Dimorphoplites niobe*, *Brancoceras* sp., *Euhoplites subtuberculatus*, *E. pricei*, *Hamites* spp. **Lamellibranchia**—*Inoceramus concentricus*. **Echinodermata**—*Hemiaster bailyi*. **Vertebrata**—Vertebra of *Ichthyosaurus* sp.

Bed 8. **Ammonoidea**—*Dimorphoplites niobe*, *Anahoplites planus*, *Euhoplites* cf. *loricatus*, *Hamites* sp.

Bed 7. **Ammonoidea**—*Dimorphoplites niobe*, *D. doris*.

Bed 6. **Ammonoidea**—*Anahoplites intermedius* Spath, *A. planus*, *Euhoplites subtuberculatus*, *Dimorphoplites* aff. *niobe*, *D. doris*, *D.* sp. nov., **Lamellibranchia**—*Inoceramus concentricus*.

Bed 5. **Ammonoidea**—*Anahoplites intermedius*, *Falciferella milbournei* Casey. **Lamellibranchia**—*Inoceramus concentricus*.

Bed 4. **Ammonoidea**—*Anahoplites intermedius*, *A. praecox* Spath, *A. splendens*, *Falciferella milbournei*, *Hoplites* sp. juv.

Bed 3. **Ammonoidea**—*Anahoplites intermedius*, *A. praecox*, *A. splendens*, *A. mantelli* Spath, *A. planus*, *Hoplites dentatiformis* Spath, *H.* aff. *paronai* Spath, *Falciferella milbournei*, *Protanisoceras nodosum* (J. Sow.), *Hamites attenuatus* J. Sow. **Lamellibranchia**—*Inoceramus* *concentricus, Nucula pectinata, 'Cardita' tenuicosta, Neithea quinquicostata* (J. Sow.), *Oxytoma* sp. **Vertebrata**—Fish otoliths and scales; tooth of *Ichthyosaurus* sp.

Bed 2. **Ammonoidea**—*Hoplites dentatus* (J. Sow.), *H. spathi* Breistroffer, *H. persulcatus* Spath, *H.* aff. *paronai, H.* aff. *rudis* Parona & Bonarelli, *H. similis* Spath, *H. canavariformis* Spath, *H. latesulcatus* Spath, *H.* spp. nov., *Hamites attentuatus, Ham.* sp. nov., *Protanisoceras nodosum, Pictetia astierianum* (d'Orb.). **Crustacea**—*Notopocorystes stokesi.* **Lamellibranchia**—*Inoceramus concentricus.*

Bed 1. **Ammonoidea**—*Hoplites dentatus.*

In addition to the above records, the **coral** *Micrabacia coronula* (Goldfuss), **annelids**, aporrhaid **gastropods**, the **scaphopod** *Dentalium* and the **belemnite** *Neohibolites* were collected from all the beds. Valves of **cirripedes** and a few nodules encrusted with **polyzoans** were also collected.

## 3. CORRELATION WITH THE FOLKESTONE SUCCESSION

Vertical sections of the Gault at Greatness Lane, Sevenoaks, Kent, and the corresponding beds at Folkestone, Kent, are illustrated in Fig. 1.

Beds 1 and 2 of the Greatness section, not previously exposed, contain *Hoplites dentatus* and *H. spathi* and are therefore correlated with the *dentatus—spathi* subzone of the *dentatus* zone, i.e. the lower part of bed I at Folkestone. Of special interest at Greatness Lane is the occurrence of several new species of *Hoplites* in bed 2, some of which form transitions from *Hoplites* of the *canavariformis* group to *Euhoplites pricei* and allies of the next higher subzone. This is taken to indicate that bed 2 at Greatness Lane represents, in condensed form, the upper part of the *dentatus-spathi* subzone at Folkestone, where these transitional forms of *Hoplites* occur, crushed in the clay.

Beds 3–7 at Greatness Lane contain *Anahoplites intermedius* and allies, as the predominant ammonites, and are clearly referable to the *intermedius* subzone of the *dentatus* zone. At Folkestone this subzone comprises the top part of bed I, and bed II, a total thickness of about 6 ft. Thus, there is a considerable thickening of this subzone in the Sevenoaks area, as noted by previous observers (Spath, 1943, p. 737; C. W. Wright, 1946; Khan, 1952; Casey, 1954).

Of special interest is the discovery of the ammonite *Falciferella milbournei* in the *intermedius* clay at Greatness Lane. This is the subject of a separate communication by R. Casey (1954).

Bed 7 at Greatness Lane is overlain by a line of phosphatic nodules (bed 8) with *Dimorphoplites niobe*. This ammonite ranges upwards through beds 9, 10 and 11, and the author follows Khan and Casey in assigning this part of the succession to the *niobe* subzone of the *dentatus* zone, i.e. bed III of Folkestone.

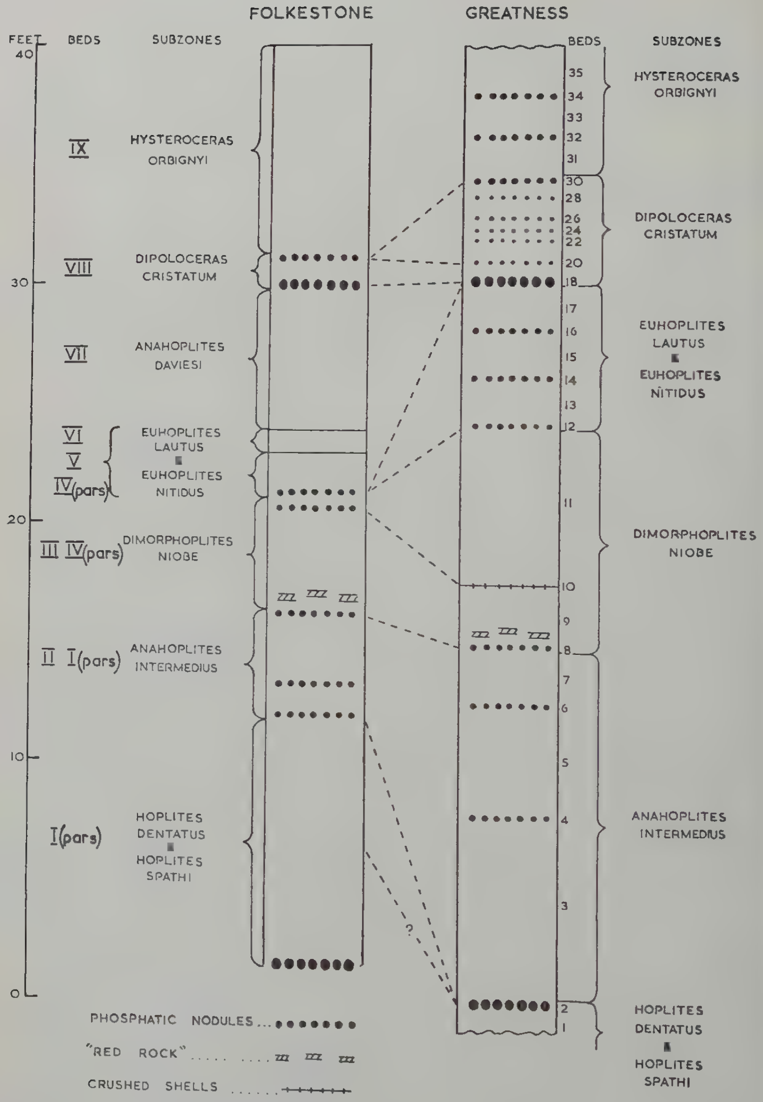

Fig. 1. The Gault succession at Greatness Lane, Sevenoaks, Kent, compared with that at Folkestone, Kent

At Greatness Lane *Dipoloceras subdelaruei* occurs abundantly in a thin seam of crushed shells (bed 10) 2 ft. 10 in. above the base of the *niobe* subzone, i.e. well within that subzone. At Folkestone, however, this ammonite occurs only in the lower layer of nodules, and in the immediately overlying clay (in bed IV), so it is suggested, therefore, that these nodules represent, in condensed form, the top 6 ft. 4 in. of the *niobe* subzone at Greatness Lane.

The greater thickness of this subzone at Greatness Lane (9 ft. 4 in., compared with 4 ft. 6 in. at Folkestone), and the occurrence of *D. niobe* in the lower layer of nodules in bed IV at Folkestone (together with a new species of *Hoplites* which occurs in the upper part of the *niobe* subzone at Greatness Lane) support this view. Thus, the lower layer of nodules together with the 4 in. of immediately overlying clay (in bed IV) at Folkestone, probably should be referred to the *niobe* subzone, and not to a separate subzone of *Dipoloceras subdelaruei*. This in no way discredits the stratigraphical use of *D. subdelaruei* which is an excellent horizon marker, at least throughout Kent.

The fawn-grey colour of the clay is a characteristic feature of the *niobe* subzone at both localities, as are the lenticles of 'red rock' at the base.

Beds 12 to 17 of the Greatness section, a total thickness of 6 ft., contain *Euhoplites aspasia* and other early forms of the *lautus* group commonly found in the upper layer of nodules of bed IV at Folkestone. It is probable, therefore, that this nodule layer represents, in condensed form, beds 12 to 17 at Greatness Lane. Further collecting is likely to reveal that the upper layer of nodules in bed IV at Folkestone, and the equivalent beds at Greatness Lane, need recognition as a distinct subzone; at present, however, they are attached to the *lautus-nitidus* subzone.

Bed 18 is the most easily recognised bed in the pit, giving rise to a conspicuous nodule band in the face. It contains a prolific fauna, the majority of species being those of the *cristatum* subzone. Compared with the *cristatum* subzone (bed VIII) at Folkestone, however, there is a relative abundance of *Dimorphoplites chloris*, *D. tethydis* and *Euhoplites lautus*, which suggests that some part of bed V of the Folkestone section is incorporated in this nodule layer. Rare specimens of *Dimorphoplites doris*, *Euhoplites aspasia* and *E. subtuberculatus* indicate that even earlier horizons may have contributed to its contents. On the other hand, it must be pointed out that no certain evidence for the inclusion of Beds VI or VII of Folkestone has been found in this nodule layer. It is probable that these latter beds are unrepresented, and that bed 18 is a condensed, and incomplete, record of beds V to VII of Folkestone.

Beds 19 to 30, which still contain *Dipoloceras cristatum* and other forms of the *cristatum* subzone, are correlated with the upper part of bed VIII at Folkestone. The equivalents of these beds at Dunton Green were incorrectly assigned to the *orbignyi* subzone by Wright (1946). At Folkestone, bed VIII is 8 in. thick, compared with 4 ft. 3 in. at Greatness Lane.

Beds 31 to 35 contain abundant *Hysteroceras orbignyi*, and are the obvious correlatives of bed IX at Folkestone, the *orbignyi* subzone of the *inflatum* zone. Only 5 ft. 4 in. of this subzone is exposed, marking the base of the Upper Gault. As at Folkestone, there is an abrupt change from the dark clays of the Lower Gault to the light grey clays of the Upper Gault.

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# Tectonic styles in the Dalradians and Moines of parts of the Central Highlands of Scotland

by B. C. KING and N. RAST

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**ABSTRACT:** Fold styles in the Central Highlands show a general increase in deformation, marked by progress from asymmetry to extreme recumbency and flattening, on proceeding across the Dalradians into the Moines. Different lithological units display widely varying styles of deformation, resulting in structural disharmony between major formations, and with progressive deformation, stratigraphic discontinuity becomes increasingly characteristic on all scales. In the Moines the banding is related essentially to planes of shear, and there appears to be no way of estimating original sedimentational thicknesses. Folding occurs predominantly along two axial directions: NE.–SW. (Caledonoid) and NW.–SE. (cross-folding). The former is ubiquitous and is represented by major overfolding. The latter is only a major phenomenon in limited areas—usually narrow belts trending NW.–SE.—and rarely involves significant overfolding on a large scale. The two systems of folding were effectively simultaneous, the axis of rotation (b-axis) of the cross-folds approximating to the direction of translation (a-axis) of the Caledonoid folds.

## 1. INTRODUCTION

THIS ACCOUNT RECORDS certain observations and general inferences made during detailed structural studies, now in progress, in a belt of the Scottish Highlands extending from Schiehallion to Braemar. Specific accounts of the various areas will be published elsewhere. Also, where appropriate, references are made to a number of other areas for which the authors have adequate structural data.

So far, interpretation of the tectonic pattern of the Highlands has depended primarily on inferences based on the stratigraphic sequence. The positive achievements in this field are largely due to Sir E. B. Bailey, whose works of especial relevance in the present account were published in 1925, 1928 and, with McCallien, in 1937. It may be noted that, according to Bailey, the stratigraphic sequence in Perthshire is also the general order in which the formations are encountered in a traverse across the Central Highlands towards the Highland Boundary (see Fig. 1, facing p. 245). A brief description of the lithology of the principal groups is given in the accompanying table:

TABLE I: **Lithology of the Central Highlands Succession**

| | |
|---|---|
| DALRADIAN SERIES | |
| Pitlochry Schist | Quartzose mica-schist, often garnetiferous. |
| Loch Tay Limestone | Thick bands of grey limestone with calcareous schist. |
| Ben Lui Schist | Fairly uniform grey garnetiferous mica-schist, often quartzose. |
| Ben Lawers Schist | Variable mica-schist and calc-mica schist, locally with bands of limestone. |
| Ben Eagach Black Schist | Dark, finely-crystalline graphitic schist with some quartzose bands. |
| Perthshire Quartzite Series | Mainly quartzite, but includes a middle member of garnetiferous mica-schist (Killiekrankie Schist) over much of the Central Highlands. |
| Blair Atholl Series | Variable sequence, with pale and dark limestones, black schists and flaggy quartzose schists. |
| MOINE SERIES | |
| Struan Flags | Pale grey, white or pink quartzo-felspathic granulites, with mica-rich layers and flaggy parting or parallel jointing. |

The general line of the Loch Tay Limestone divides the region into two contrasting areas: to the south-east the formational units show great persistence and regularity across the Highlands, whereas to the north-west the area is manifestly characterised by more complicated tectonics. Here correlation of the major formations is often difficult, and clearly elucidation of the structure within these larger units is impossible unless a correct assessment of the tectonic styles can be made.

Tectonic style can be appreciated only by observation on all scales. More especially this is true of the structures that can be studied closely and measured on individual outcrops, for the minor structures form an integral part of the movement pattern by which the major structures have been

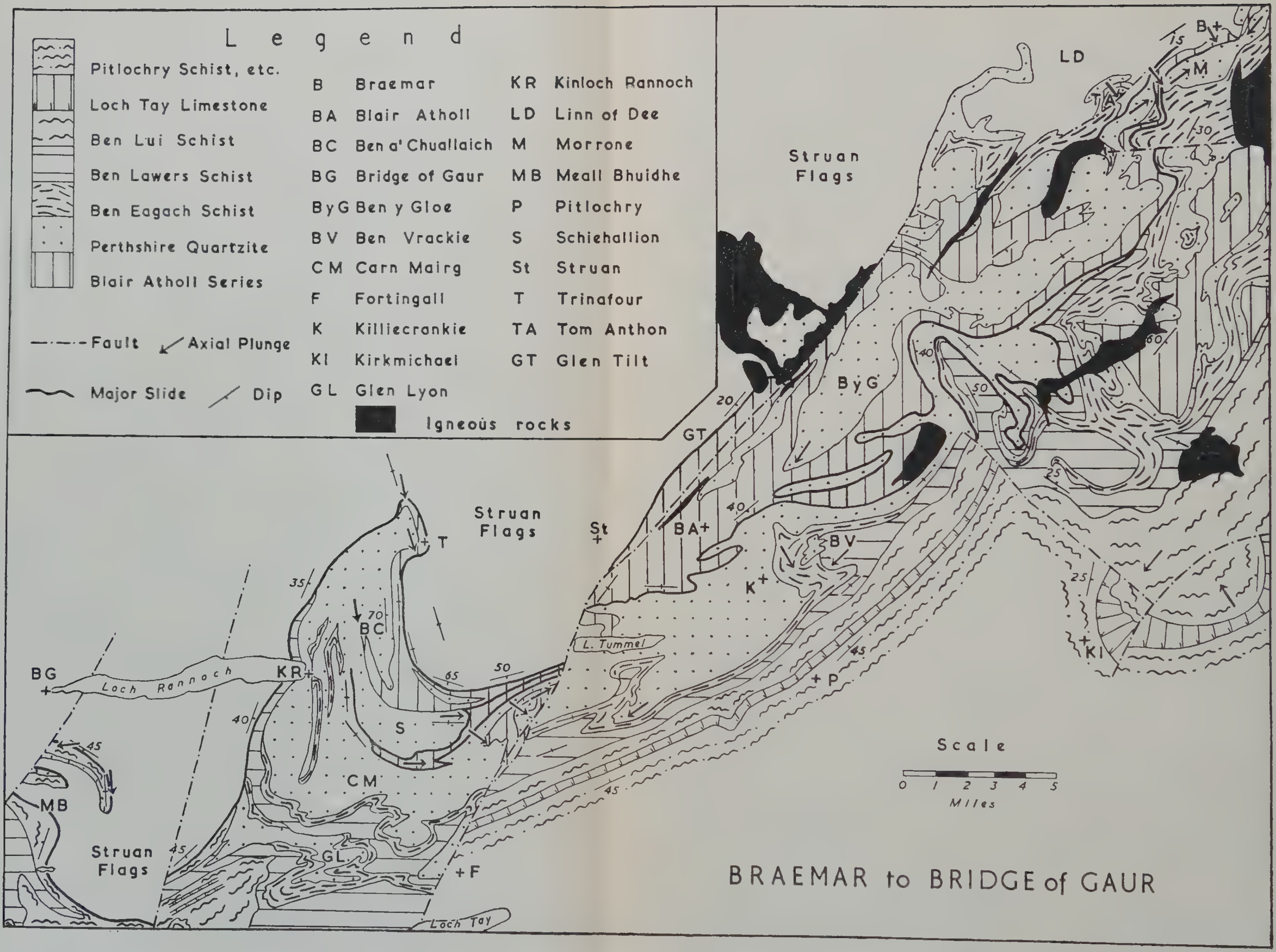

Fig. 1. Generalised geological map of the Central Highlands from Braemar to Bridge of Gaur, largely after Bailey & McCallien, 1937.

produced (McIntyre, 1952b). Thus, the almost horizontal Loch Tay Limestone of Glen Ogle (between Killin and Lochearnhead) is characterised by numerous flat-lying folds which are analogous in form to the major recumbent structure inferred to explain the disposition and mutual relations of the Dalradians in the South-eastern Highlands (the 'Zone of Inversion') (Bailey, 1925). Moreover, the recumbency of the observable minor structures necessarily involves the postulate of major recumbent folding. As long ago as 1897 Clough inferred large-scale recumbent folding in Cowal, not only from the disposition of lithological units, as seems often to be assumed, but also from the kinematics revealed by consideration of structures of small and intermediate-scale.

## 2. TECTONIC STYLES IN THE DALRADIANS

South-east of the Loch Tay Limestone it appears to be generally true that original stratigraphic relations between formations, including individual beds, are often preserved. Considerable repetition by isoclinal folding is usually demonstrable, as at the south end of Loch Lomond, but schistosity, as it develops, is often in agreement with original bedding, in the main because the fold style shows long limbs approximately parallel to the axial planes (Clough *in* Gunn *et al.*, 1897, pp. 9, 10, 13).

The complexity in the major structure between the Loch Tay Limestone and the Moines (Struan Flags) is immediately apparent when any attempt is made at stratigraphic correlation. In his structural interpretations, Bailey necessarily invokes sliding, primarily to account for the anomalous juxtaposition of formations which can be shown to have been separated more or less widely in the original stratigraphic sequence. Especially convincing is the frequent observation of extremely attenuated representatives of part, or all, of the intervening formations.

The style of the smaller-scale structures shows that, in general, the amount of deformation increases north-westwards across the Dalradians and into the Moines, so that the latter, despite their apparent simplicity of structure, are the most deformed assemblage (Fig. 2 C). Not only do fold styles show increasing recumbency and compression, but extensive areas are affected by two sets of folding on axes approximately at right-angles to each other (p. 256). The rapid variations in formational thickness, and the stratigraphic discontinuities revealed on the map, are primarily tectonic and not explicable in terms of sedimentational variation as has been sometimes supposed. Different formations have responded to movement in very different ways, so that varying styles of structure, only attributable in part to varying stages of deformation, can be recognised in different formations at the same locality. The more important lithological types will be considered separately, therefore.

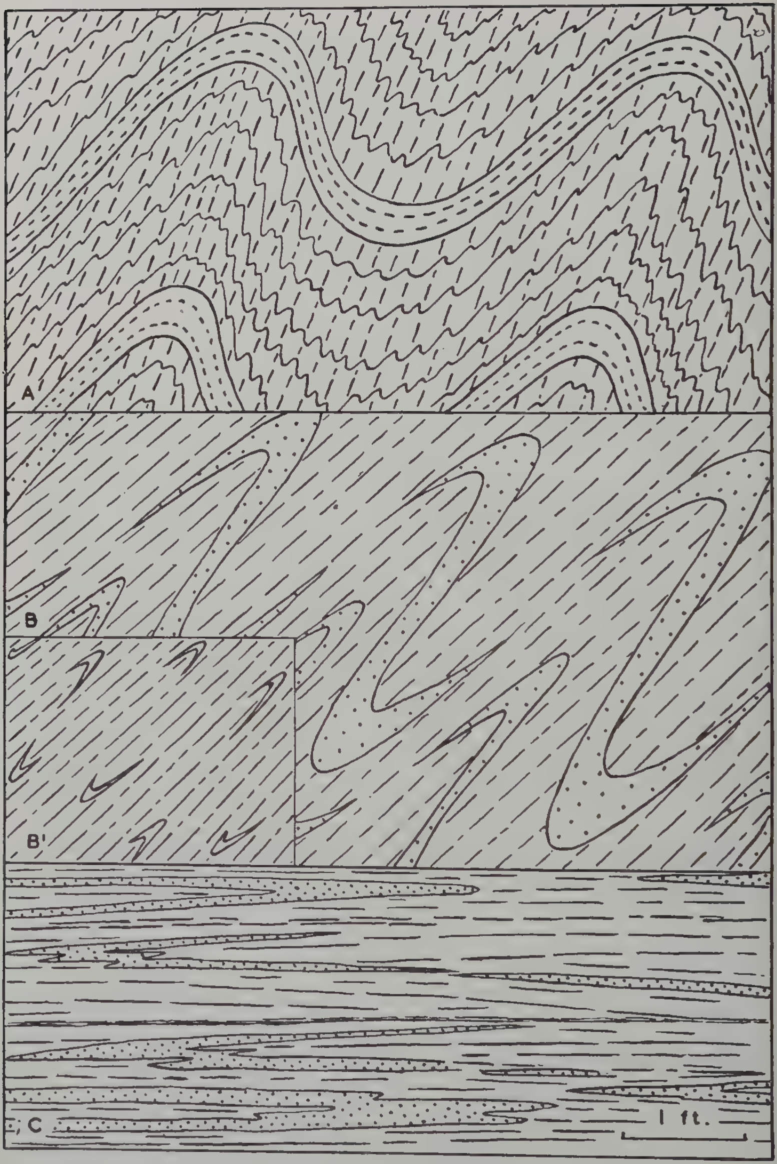

Fig. 2—*see opposite*

(a) **Quartzites.** Original depositional structures are preserved more commonly in quartzites than in other types of rock. Thus, pebbles and bedding, including current bedding, are often recognisable. Nevertheless, the beds are usually folded on all scales permitting of direct observation (Fig. 3 A). The actual complexity of the structures in quartzites is easily overlooked because folding is locally confined to belts of restricted width, separated by areas showing simple undulations. These features are illustrated on Morrone, about two miles south of Braemar. Here folding in the quartzite becomes progressively more intense towards its junctions with other formations which lie to the north and south. The folds become more compressed, and often strong rodding, or other linear structures, are developed parallel to the fold-axes at an advanced stage of deformation. During folding, quartzite typically shows extreme thickening of individual layers in the closures of the folds, the process being accompanied by obliteration of original structures, and often by recrystallisation, to give massive white quartzite. On a regional scale the great developments of quartzite on Schiehallion, Meall Dubh (one mile north of Kinloch Rannoch), and Ben y Gloe, are largely the result of tectonic thickening in complex fold-cores.

Equally apparent in the field is the consistent attenuation of corresponding limbs in a series of quartzite folds, the attenuation becoming more marked with increasing compression of the fold style. Original structures give way to a close platy layering, and often there occur bands of flaky quartzites which have a schistose appearance although they contain very little mica. Clearly these phenomena are to be explained as resulting from increasing shear-movement between layers in the limbs of the folds during the development of the latter.

(b) **Schists.** In schists of uniform lithology the structural significance of the schistosity is not ascertained easily, and the approximate coincidence of schistosity with the general disposition of adjacent formations may lead to the assumption that schistosity is parallel to bedding. However, where the schists contain folded psammitic or calcareous layers it is seen that a new planar structure, agreeing approximately with the axial planes of the folds, becomes, by degrees, the only schistosity of the rock, as the folds themselves become more strongly compressed (Figs. 2 B, 3 C). The relationship between the schistosity and axial planes is often shown by the presence of isolated, tightly-compressed, relic fold-closures (Fig. 3 B).

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Fig. 2. A and B illustrate, diagrammatically, the development of axial plane schistosity, with systematic attenuation of fold-limbs and thickening of layers of quartzite at fold closures. In B, only the apices of folds remain as indicators of the tectonic significance of the schistosity. C shows the Moine style of folding, with extreme elongation and flattening (Tom Anthon, west of Braemar). Schistosity and banding are not always precisely coincident, so that the oblique intersection of these structures reveals, even in the absence of fold closures, that the general layering is of tectonic origin.

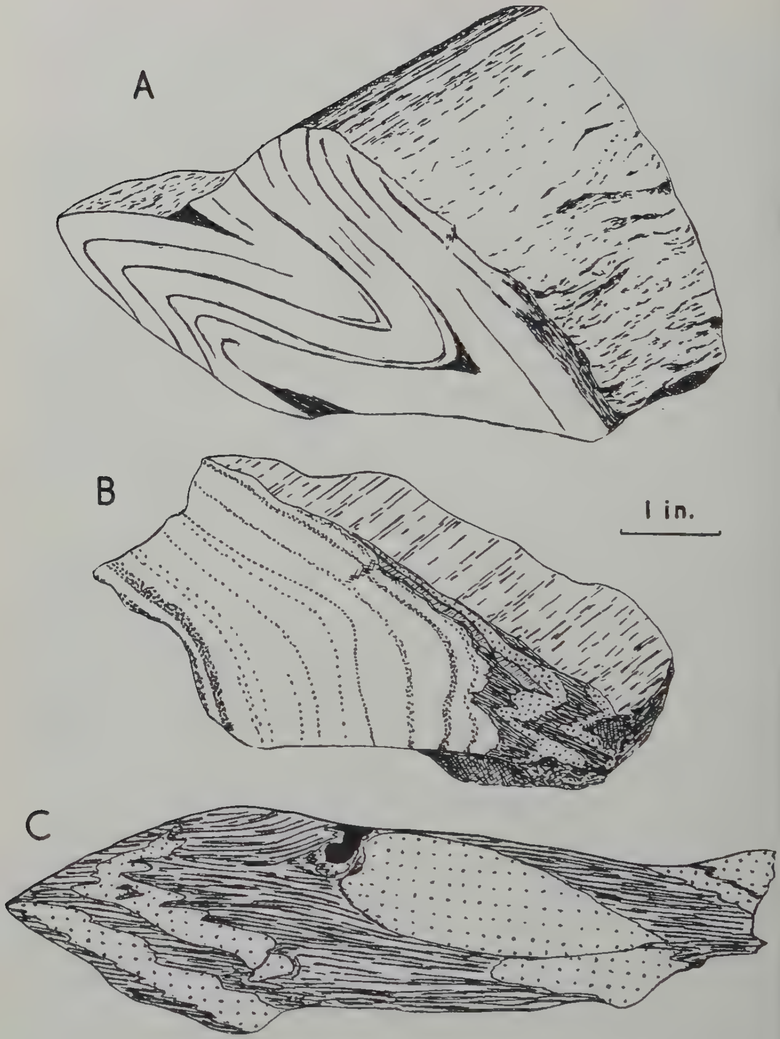

Fig. 3. A. Fold style in quartzite: fine rodding agrees with axial direction of 220°, plunge 5° SW. From Morrone, near Braemar (KB 105).
B. Fold closure terminating intercalation of quartzite in coarse mica schist. Relations between schistosity and axial plane, and between lineation and fold axis are illustrated. From thrust zone (slide) below quartzite, north slopes of Morrone, Braemar (KB 11).
C. Quartzite and schist occupying fold closure. The quartzite shows thickening at apices of miniature folds and partial disruption into lenticles along planes of shear which are sub-parallel to axial plane of the fold. From Lassintullich, near Kinloch Rannoch (SR 130).

These stages in the development of axial plane schistosity may be seen in very many localities. On a broad scale they are shown by a comparison of structures in the Ben Lawers and Ben Eagach Schists in Glen Lyon with those in the same formations to the south-west of Ben Vrackie.

It is evident that extreme caution must be exercised in assuming that layering showing variations of lithology in schists bears any direct relation to original depositional banding. Clough was well aware of this problem (Clough *in* Gunn *et al.*, 1897, pp. 20, 22, 24–5). Even on a larger scale, apparently normal intercalations of quartzite or limestone often terminate in recognisable fold-closures where the bands can be traced (Fig. 3 B, C). Examples are numerous: among them the schists intervening between limestone and quartzite one mile south of Braemar and the Killiekrankie Schists to the south-east of Ben a'Chuallaich (near Kinloch Rannoch). These occurrences emphasise the necessity for establishing tectonic style before interpreting intercalatory junctions as original lithological transitions. Indeed, it is questionable whether there exist in the Central Highlands any transitions which can be proved to correspond directly with original sedimentational intercalations. The discovery of a single fold-closure at the termination of a band suffices to show that, even if an original transition existed, points on either side of junctions in the detailed pattern bear no ascertainable relation to their positions in the sediments as deposited at first.

Where the schistosity trends across a major lithological boundary it is especially clear that the transitional rocks represent mechanical intercalations. Nevertheless, even where a passage is seen along the strike, appreciation of the detailed tectonic style may indicate the probability that axial plunge of close and complex folding is responsible for gradually elevating or depressing a particular formation. Such relations may be misinterpreted easily as examples of lateral variations in original sedimentation. At a number of localities to the south-west of Braemar close folding of this type has given rise to lateral passages from siliceous flags to ribbed limestones. In the Carrick Castle area, Clough (*in* Gunn *et al.*, 1897, p. 200) noted that distinctive horizons, when traced laterally, become mixed with adjacent formations, and suggested that this was due to acute folding, with axes parallel to the prominent foliation.

(c) **Limestones** are particularly revealing in connection with tectonic style, more especially where they contain closely-spaced siliceous layers. In such formations, owing to the great difference in response to deformation manifested by the two components, a sequence of stages in the tectonic history is often displayed in a single outcrop. Frequently, the siliceous layers are partially preserved from deformation by the effectively plastic behaviour of the limestone. The siliceous bands show intermediate stages in the development of the folds, whereas in the limestone the folds may show

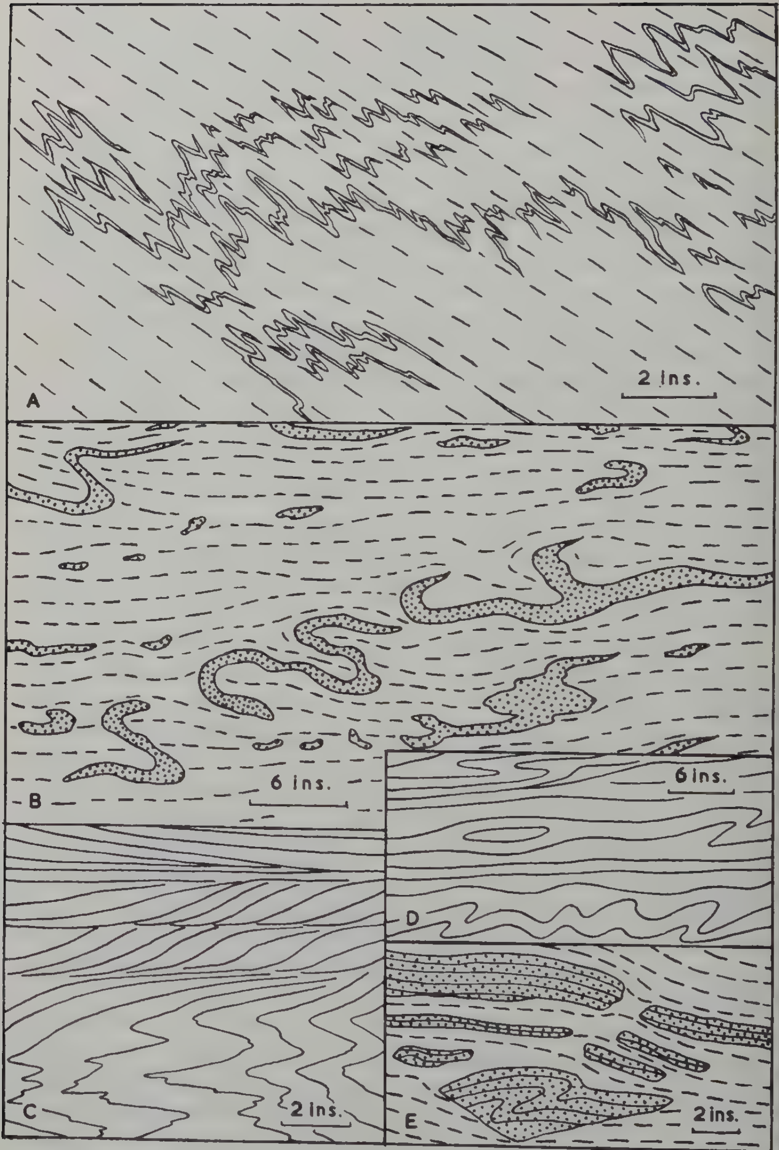

Fig. 4—*see opposite*

partial, or complete, destruction by shearing (Fig. 4, and Balk, 1936, figs. 20–3). These phenomena are well displayed by the Blair Atholl Limestone, as in Glen Tilt, to the south of Braemar, and near Lochan Daim, one mile north of Schiehallion. The siliceous layers, after folding, gradually lose their continuity, ultimately being represented by isolated tectonic inclusions which are often recognisably fold apices. The adjacent limestone displays exaggerated folds of which the apices are finally lost in shear. The final stage may show what appears to be uniformly bedded limestone, closely simulating an original depositional structure. That this simplicity of structure is only apparent is indicated by the presence of occasional tectonic inclusions, and of obliquely convergent layering, not unlike current bedding in quartzites, as well as by the occurrence of intense folding in underlying or overlying horizons. Similar features are seen in the highly-calcareous Ben Lawers Group, where it is strongly deformed, as to the west and south-west of Ben Vrackie.

These differences in behaviour help to explain why the main Dalradian groups retain their essential internal unity, despite the amount of folding to which they have been subjected. Formations have been folded disharmoniously, a phenomenon that can be demonstrated easily in the field on small and intermediate scales (Peach *et al.*, 1909, fig. 1). Barrow's postulate of concertina-folding, the formations being folded upon themselves, does accord with reality in some measure, although it was inferred primarily on stratigraphic grounds (Bailey, 1934, p. 505).

It is abundantly apparent that with increasing deformation, junctions on all scales have progressively less significance as indicators of original stratigraphic boundary surfaces. At the more advanced stages of deformation, virtually every junction, whatever the scale, has become a tectonic one (McIntyre, 1950a, 1951). Indeed, slide (fold-fault) tectonics, invoked by Bailey to explain major stratigraphic anomalies, are characteristic of all scales on which observation is possible. The most notable evidence, on a small scale, is the systematic attenuation of layers in corresponding limbs

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Fig. 4. Tectonic styles in the limestones south-westwards from Braemar.

A. General banding of limestone, agreeing with axial planes of tiny plications shown by thin siliceous ribs. Axial direction 160°; plunge 20° SSE.

B. Original siliceous layers largely represented by thickened and disconnected fold closures. Banding in the limestone is deflected locally by the larger siliceous masses, but in general, agrees with axial planes of the folds. Axial direction 210°; plunge 5–15° SSW.

C. Closely compressed folds in homogeneous limestone, showing loss of apices in shear in upper part of sketch. Axial direction 150°; plunge 25° SSE.

D. Banding in homogeneous limestone, showing overfolds with sense of rotation in opposite directions in different layers. Note fold closure isolated by plastic flowage. Axial direction 150°; plunge 30° SSE.

E. Siliceous layers disrupted to form tectonic inclusions preserving simple fold style, and showing rotation by plastic flowage of surrounding limestone.

of a series of folds. Conversely, however, in the Dalradians there is the evidence of tectonic thickening of formations in fold closures—notably quartzites, but also limestones—as well as the repetition of formations by close folding. Consequently there is no way in which a reliable estimate can be made of the original thickness of any of the Dalradian formations. It is not unlikely, however, that, in the region as a whole, repetition by folding and tectonic thickening was more important in increasing the apparent thickness of formations than was sliding in producing attenuation.

Unless due allowance is made for folding, it is easy to assign quite improbable thicknesses to formations in many localities. Repetition by folding is demonstrable by direct observation in the quartzite masses of Morrone and Beinn a'Chuallaich. Even in the Glencoe Quartzite, south of Loch Leven in the Ballachulish region (where numerous observations of current bedding showing consistent 'younging' to the west, considered in conjunction with a vertical or near vertical dip, give an apparent thickness of some miles) the possibility of repetition by folding cannot be excluded (Green, 1931, p. 529). The systematic destruction of the original structures in the eastern limbs of a series of isoclinal folds by thinning and shearing is entirely compatible with what may be demonstrated, on a small scale, in many other localities. Indeed, bands of platy, or schistose, sheared-looking quartzite are not uncommon in the Glencoe Quartzite. Barrow carried his postulate of repetition by folding to the extreme that he inferred folding was responsible wherever a bed of particular rock type is repeated (Barrow, 1904, pp. 408, 416).

Structural disharmony between formations which differ in lithology is of increasing significance with progressive deformation, and can be appreciated directly in the field. A spectacular example is seen to the west of Ben Vrackie, where numerous enclosures of quartzite, ranging in size from a few feet to masses which can be represented on the map, are found within black schists of the Ben Eagach Group. The schists display tightly compressed fold-closures as discontinuous relics paralleling the prevailing axial plane schistosity. The latter is often truncated abruptly by, or deflected against, blocks of quartzite which show much simpler fold patterns. On a much larger scale, detailed mapping shows that the fold structures in the quartzites to the south and south-west of Braemar are largely discordant with the structures and disposition of the underlying formations, which are generally limestone.

Variations in tectonic style, or of intensity of deformation, shown by the same formation in different localities may so alter the appearance of the formation as to make recognition difficult. An example is provided by variations in the Ben Lawers Schists as seen in Glen Lyon, on Ben Vrackie and near Kinloch Rannoch. The localities are listed in order of increasing deformation, the rocks becoming simultaneously more schistose, while hornblende, garnet and mica increase at the expense of calcite. In the Blair Atholl Limestone, to the south-west of Braemar, progressive deformation can be traced, with the eventual production of tremolite schists. Variations in thickness and lithology, especially in the relative development of schists within the group, are determined by tectonic factors rather than by differences in original sedimentation.

The extreme result of deformation is represented by certain lustrous, coarsely-crystalline micaceous schists, which are characteristic of many major slides, where evidently they are the product of intense localised shearing. The Beoil Schist, at the Moine–Dalradian boundary to the north of Schiehallion, is of this type. It has tectonic, rather than stratigraphic significance, for demonstrably it has been formed predominantly by contribution from Moine formations as they become involved in the slide. Virtually identical schists characterise the slides, or thrust zones, to the south and south-west of Braemar. Here their tectonic origin is emphasised by the fact that at various points along their course they lie between quartzite and limestone; between quartzite and Moine; or between Moine and Moine. Nevertheless, it can be shown that they have been formed largely by extreme attenuation and shearing of the Blair Atholl Group. On a small scale, the development of micaceous layers along strain slips, as first described by Clough (*in* Gunn *et al.*, 1897, p. 20), is closely analogous. Indeed, on the same scale, strain slips themselves correspond to thrusts or slides in replacing limbs of miniature folds, as Clough clearly appreciated (*op. cit.*, pp. 22, 24). F. E. Suess (1931, p. 78) recognised the tectonic significance of certain schists with large micas, while both Barrow and Cunningham Craig (1912, pp. 26, 28, 41) were well aware of the importance of progressive deformation in determining the lithology of corresponding formations at different localities.

## 2. TECTONIC STYLE OF THE MOINES AND THE MOINE–DALRADIAN BOUNDARY

Very generally, workers in the Highlands have considered that repetition by isoclinal folding is responsible for the wide areas occupied by Moines which show uniform strike and dip (Barrow, 1904, p. 414; Peach *et al.*, 1913, p. 56; Read *et al.*, 1926, p. 115; Read, 1931, pp. 28, 34; Phemister, 1948, p. 22). Nevertheless, little has been recorded as to the precise form of these folds, and few examples of actual fold styles have been studied (McIntyre, 1950, 1950a; Wilson, 1953; Sutton & Watson, 1954). Moreover, it appears to be generally inferred that, despite the folding, the individual layers in the Moines correspond to original beds, and that they are disposed in much the same way as those of any unmetamorphosed sedimentary sequence. However, numerous observations made on the

Moines in Perthshire and Aberdeenshire show that, at least in these areas, no simple relation can exist between present and original structures. Thus, in localities as widespread as Loch Rannoch, Glen Tilt north of Blair Atholl, and the Linn of Dee, west of Braemar, the Moine granulites are characterised by extremely flattened recumbent folds (Barrow & Cunningham Craig, 1912, pl. 5). The limbs are so compressed as to be virtually or completely parallel, while closures are not abundant on account of the great amplitudes of the folds when compared with their thicknesses from limb to limb (Peach *et al.*, 1913, pp. 76, 85). In relation to the folds, the general banding of the granulites conforms to the disposition of the axial planes, while the schistosity in the more micaceous layers, and the conspicuous flaggy jointing, are also in effective agreement (Figs. 2 C and 5). This general banding is not involved in the minor folding, but contains the folds. Characteristically, one or both fold limbs shows attenuation, so that the closures may appear isolated within the bands; even the closures themselves may be represented only by obliquely convergent layering.

Thus it is apparent that in those bands which contain folds, at most the layering can bear only a very indirect relation to original layers of sedimentation, for the disposition of all points within the present structure must be quite unlike that of corresponding points in the original structure,

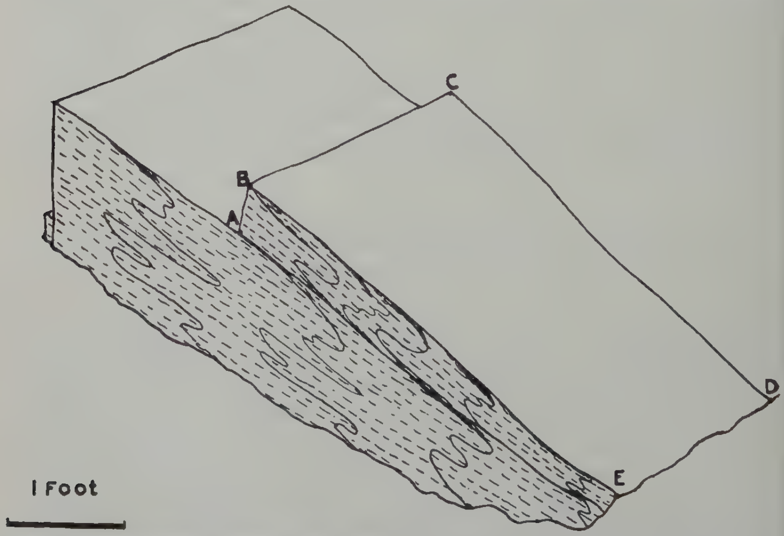

Fig. 5. Tectonic style of Moine granulite from loch shore about one mile west of Kinloch Rannoch. The upper surface is defined by joint planes (e.g. BCDE). These planes show a close dependence on shear planes, as revealed by the pattern of the small-scale folds, and are sub-parallel to the axial plane schistosity.

and there is no way of establishing what that former disposition was. Nevertheless, it is likely that within parts of the present structure there exist elements which preserve their original relative positions.

It is important to note that, generally, observation of detailed structures in the Moines is possible only on exceptionally clear, water-worn surfaces (Barrow *et al.*, 1905, pp. 67–8), but even in the most favourable circumstances considerable thicknesses have been examined in which visible folds are exceedingly rare, or quite absent. These may then be succeeded by bands containing numerous fold-closures, every layer in the structure corresponding to one or both limbs of a fold.

Often it appears probable that the absence of actual folds from certain bands is merely because the apices of the closely compressed folds have been lost in shearing or sliding. Sometimes the penultimate stage may be recognised where layers are seen to be converging on one another obliquely, giving a structure that might easily be mistaken for current bedding (Clough *in* Gunn *et al.*, 1897, p. 25). Moreover, the actual complexity of even the uniformly-banded types is sometimes clearly indicated by the presence of tectonic inclusions, as in Glen Tilt, three miles north of Blair Atholl. The characteristic banding of the Moines is thus regarded as related to innumerable planes, or narrow zones, of shearing or sliding along strongly compressed fold-limbs, and thus implies extensive lateral transport. Indeed, on quite obvious grounds, the extraordinary regularity of dip and strike in the Moines, as representing an original structure, is suspect.

Whereas tectonic thickening of certain formations at fold-closures is characteristic of the typical Dalradian style of deformation, at the more advanced stage shown by the Moines, extreme compression and shearing have led to more or less attenuation. Thus, while in the Dalradians even an approximate estimate of original thickness is difficult, in the Moines any kind of estimate is impossible.

It is the great lithological uniformity of the Moines which renders difficult the elucidation of their fundamental tectonic style, although doubtless this very uniformity has contributed largely to the sameness of their response to deformation. However, at boundaries with the Dalradians, the actual style of folding is often quite apparent; the presence of greatly attenuated and highly compressed folds is revealed by the incoming of layers of markedly different lithology from the typical Moine rocks (Fig. 2 C). Excellent exposures which show this occur three miles south of Bridge of Gaur, and on Tom Anthon, three miles west of Braemar. At these localities the Moines gradually become atypical by the appearance of numerous flattened infolds, on cursory examination resembling intercalations of other rock types, such as quartzite, schist or calc-silicate rocks. At Tom Anthon, in particular, it is clear, from field mapping, that the infolds are formations of the Dalradians.

There are, indeed, great variations in the Moine–Dalradian boundary. In places, as to the north of Schiehallion, where different members of the Dalradian sequence are brought systematically against the Moines, this boundary is a major slide and is very well defined. Elsewhere, although various Dalradian formations are involved, the actual junctions are marked by complex folded transitions. A remarkable feature is that the Dalradians in such transitions and indeed sometimes for some distance from the boundary (whether transitional or abrupt), commonly partake of the same tectonic style as the Moines themselves—a phenomenon that often renders difficult the identification of the Dalradian formations involved. In the Braemar area it is clear that the Perthshire Quartzite and the Blair Atholl Group are the associated formations, but at Bridge of Gaur the Dalradians involved may be assigned with less certainty to the Ben Lawers and Ben Lui Schists. To the north and north-west of Kinloch Rannoch, rocks later recognised as Perthshire Quartzite, Ben Eagach and Ben Lawers Schists (Anderson, 1923), were assigned originally to the Moines (*Geol. Surv.*, Sheet 55) on account of an apparent lithological similarity resulting from a similar tectonic style.

Fifty years ago Barrow (1904, p. 415) was aware that the Moines display a peculiar style of deformation, in which associated Dalradians share, and to which he applied the term 'Moine phase'. Also he was convinced that Moines and Dalradians are interfolded at their junctions, and referred to the sections in Glen Tilt (especially Gilbert's Bridge) in evidence. However, it seems he was satisfied that repetition of distinctive horizons was indicative of folding, but Bailey (1925, pp. 691–2) was equally convinced that at Gilbert's Bridge the succession is a normal sedimentary transition. In fact, careful search reveals close folding.

Progress from a typical Dalradian style of folding to a Moine style of folding involves increasing compression and attenuation of the folds, so that fold limbs and axial plane schistosity become effectively coincident. In mechanical terms, this seems to correspond to a gradual rotation of the axial planes into a more recumbent position, so that compression perpendicular to these planes is replaced by shear acting along them. The structures displayed along many of the slides and thrust zones may be regarded as of exaggerated Moine style in which shear movement has been unusually great within a limited thickness of rocks, whereas in the Moines innumerable smaller movements occurred throughout a much greater aggregate thickness.

## 3. DIRECTIONS OF FOLD AXES

Observation on all scales reveals the presence of two predominant fold-axial directions, which affect both Moines and Dalradians in the Central

Highlands. These axes trend approximately NE.–SW. and NW.–SE., and the associated structures may be termed 'Main' or 'Caledonoid' folds, and 'Cross' folds, respectively. In general the two directions are at right-angles to each other, and this relationship appears to be preserved despite appreciable variations in actual trend from one district to another. Thus an analogy is apparent with the 'double system of folding' well known in the Moines of the Northern Highlands (Peach *et al.*, 1907; Phemister, 1948, p. 23).

(a) **'Main' or 'Caledonoid' folds.** On a regional scale, the trend of the formations indicates that the major direction of fold-axes is NE.–SW. Minor folds on these axes are ubiquitous, the degree of recumbency and compression increasing, in general, into the Moines. The most widespread schistosity develops parallel to the axial planes of these folds. Apparently the latter are to be correlated with the major recumbent folds that must be invoked to explain the regional disposition of formations. The sense of movement shown by the style of the minor folds, and to be inferred for the major folds, is effectively uniform throughout belts of great lateral extent from north-east to south-west.

Superimposed on the recumbent folding there can be recognised, on all scales, a series of folds having steeply inclined axial planes, but with the same NE.–SW. axial direction (Bailey, 1916, p. 83). On a regional scale these are represented by open, 'mappable' folds (cf. the Ben Lawers syncline), which were, indeed, the only major folds recognised by those who did not admit of large-scale recumbent folding in the interpretation of Dalradian structures (Green, 1931). In the Moines, however, wherein significant lithological variation is largely wanting, the style of the small-scale folding is often the only indication that the fundamental structures are much more complex than the simpler, superimposed folding would suggest. It seems likely that, on a major scale, the Moines are actually characterised by strongly compressed recumbent folds, with attendant slides and thrusts, and large-scale stratigraphic discontinuities, comparable with those demonstrable in the lithologically more diverse Dalradians.

On a small scale the 'refolding' is often apparent, as where closely compressed folds are thrown into undulations, e.g. in the Moines or the adjacent Dalradians. In schists, corresponding crenulations sometimes lead to the development of fracture cleavage or strain slip, which in places becomes a new schistosity (Clough *in* Gunn *et al.*, 1897, pp. 24–6). As in the Killiekrankie Schists of Allt Mor, one mile south-east of Schiehallion, and in the schists of the Blair Atholl Series immediately to the south-west of Braemar, full analysis of small-scale structures in limited areas, often reveals deformation structures of 'second' or even 'third order', to use the terminology of Greenly (1919, pp. 196–8).

Lineations are common which agree with the NE.–SW. axial direction of folding. They are of several types: puckering on planes of schistosity; intersection of fracture cleavage (strain slip) with schistosity or bedding, and 'rodding'. The last-named is found in quartzites, as on Morrone, where the associated folds are strongly compressed, but is not common.

(b) **Cross-folds.** The presence of folding in the Moines on NW.–SE. (or WNW.–ESE.) axes, in addition to the regional folding on NE.–SW. (or NNE.–SSW.) axes, has been appreciated from the time when the series was first investigated (Peach *et al.*, 1907, p. 601). The occurrence of a prominent lineation, rodding or mullion structure, in association with the 'cross-folding', was also recognised.

Important results of the present investigations in Perthshire and Aberdeenshire are the realisation that cross-folding is found not only in the Moines, but also in parts of the Dalradians, and that both cross-folding and Caledonoid folding are often present in the same locality, and can often be recognised in the same exposure. Indeed, it is possible to collect specimens in which a given band is affected simultaneously by both directions of folding (Fig. 6).

Small-scale cross-folding is indeed widespread, and has been recorded throughout the area being investigated. In general, however, it is confined to the north-west of the outcrops of the Loch Tay Limestone[1] but its development shows wide variations, not only from one locality to another, but also in regard to the formations affected. Thus, to the south and south-west of Braemar the quartzites show only NE.–SW. folds, while in the limestones especially the cross-folding is predominant. Both systems of folds are displayed in the Ben Lawers Schists of Ben Vrackie and Glen Lyon.

Though in certain localities, such as the western side of Ben Vrackie, the cross-folding is merely predominant, in others it becomes the only folding displayed on any visible scale, as within the Dalradians and immediately adjacent Moines to the north and north-west of Schiehallion. Also it is dominant in the region around Grantown-on-Spey, as described by McIntyre (1951b). These localities of exclusive, or dominant, cross-folding approximate to belts trending NW.–SE. (or NNW.–SSE.) which affect Moines and Dalradians alike. Even more significant is the fact that, in these belts, the cross-folding is not merely a small-scale phenomenon, for it is matched by major folding which is responsible for the trends of the main rock formations displayed on the map. These belts may be recognised clearly on maps of the Geological Survey from the distribution of strikes trending NW.–SE. or NNW.–SSE., with steep or vertical dips. In this way the belts are equally traceable in the Moines wherein the uniform lithology renders them otherwise undetectable (Crampton *in* Peach *et al.*, 1913, pp. 56–8).

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[1] More recent investigations have revealed small-scale cross-folding throughout large tracts of southern Argyll. It seems likely that cross-folding on this scale may prove to be ubiquitous.

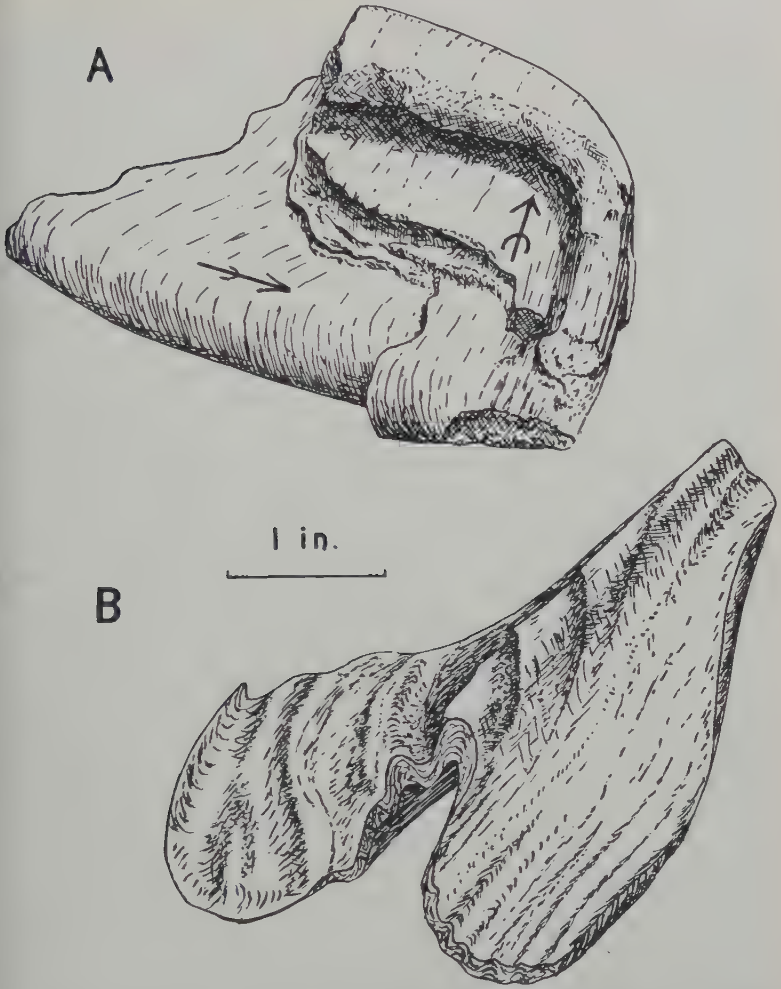

Fig. 6. A. Siliceous band disrupted to form tectonic inclusion in limestone and showing folding on two axial directions: 215°; plunge 5° SW., and 130°; plunge 20° SE. The latter is accompanied by a well-marked lineation. Tomintoul, Braemar (KB 7). B. Fold in schist showing refolding on second axial direction intersecting first axial direction at an oblique angle. Beinn a'Chuallaich, near Kinloch Rannoch (SR 5).

Through asymmetry and recumbency, the small-scale cross-folds show stages of development to extreme compression comparable with those of Caledonoid trend, although the same style is not uncommonly shown by both where the two systems occur together. However, at the extreme stage of deformation displayed by the Moines, both systems of folds are intensely compressed. An important corollary is that the axial planes of both, and consequently the related schistosities, are coincident. Although it is extremely difficult to obtain adequate information on the folding in the Moines, for reasons already given (p. 255), folding on two axial directions has been observed in many localities, and both systems display essentially the same style. Where the rocks show layering, with the characteristic low south-easterly dips, both systems of folds are correspondingly 'flat-lying'. In this connection, it is interesting to observe that, around Altnaharra in Sutherland, Read (1931, p. 30) recorded the presence of 'small-scale flat folding on axes pitching south-east' (see also Wilson, 1953, pp. 131–3, 140). The presence of the cross-folds alone in any particular locality, as in Glen Tilt, cannot be taken as implying that Caledonoid folding is absent, for it is possible that the folds are so compressed, or even sheared out, that they are incapable of detection. In those belts where the cross-folding manifests itself on a major scale, by the disposition of the banding at high angles with NW.–SE. strikes, the analogous small-scale folds show correspondingly steeply-inclined axial planes, as on Beinn a'Chuallaich, to the north of Schiehallion (see also Peach *et al.*, 1913, p. 56). The axial direction of both major and minor folds remains constant, the plunge agreeing with the regional dip in the Moines at localities away from the vertical beds.

Rodding, or mullion structure, is associated especially with the cross-folding, the two structures often being obviously related (Phemister, 1948, p. 23; McIntyre, 1950, 1951a; Wilson, 1953, p. 130). The Moines provide typical examples, but the structure is also found where the cross-folding dominates the pattern of the Dalradians, as in the quartzites around Beinn a'Chuallaich (Bailey & McCallien, 1937, pp. 103–4). It is also noticeable that where both systems of folding affect a single horizon, as in the limestones near Braemar, a lineation or rodding is associated only with the cross-folds (see Fig. 6 A).

Whereas some of the large-scale structures associated with the cross-folding are isoclinal folds similar in style to the small-scale folds (those in the Dalradians to the north of Schiehallion being easily recognised examples), the majority are comparatively simple in style. The most usual (including the general pattern of the cross-fold belts) appears to be essentially a 'monocline' in which the median limb is vertical, or somewhat overturned, and corresponds to the belts of vertical or steep dips. By comparison with findings in the Northern Highlands, these major structures appear to be analogous to the L-shaped or Z-shaped folds of intermediate scale described by Wilson (1953, p. 122). Crampton (*in* Peach *et al.*, 1913, p. 56) significantly stated that, in the Ben Dronaig area of central Ross-shire, 'the accumulated effect of this vertical folding causes the pelitic gneiss to plunge suddenly to a lower level along this boundary line, which terminates the belt of pelitic gneiss in a manner that simulates the effect of a monoclinal fold'.

On a regional scale, the broad structures associated with the cross-folding are especially revealed by the form of the Moine-Dalradian boundary. Thus, near Tomintoul (Banffshire) the Dalradians terminate against Moines along a junction of NW.–SE. trend, almost at right angles to the regional trend of the boundary. Around Schiehallion, and to the south of Bridge of Gaur, triangular areas of Dalradians make abrupt north-westerly penetrations into the general area occupied by Moines. It is significant that each of these localities coincides with a belt in which NW.–SE. folding is dominant on all scales. The direction of movement about the NW.–SE. axes can be ascertained from the style of folding in these localities. Thus, to the north of Schiehallion, the general plunge is to the south-south-east and Moines have been translated over Dalradians in a south-westerly direction. Indeed, as Bailey & McCallien have clearly shown (1937, p. 106), Dalradians and Moines are here involved in a major recumbent structure with overfolding of some one and a half miles. The symmetry of the triangular area occupied by Dalradians is, in itself, a reflection of the sense of movement. By analogy, the Dalradian triangle to the south of Bridge of Gaur suggests that movement was here in the opposite sense from that at Schiehallion, but the relations are obscured by infolds of Moines and by major faulting. In the Grantown-on-Spey area, McIntyre infers movement in the upper layers to the south-west. A similar structure is suggested, to the south of the Linn of Dee (six miles west of Braemar), from the trend of the formations shown on the map.

Wholly within the Dalradians are the complex structures developed around Ben Vrackie. Observation shows that NW.–SE. folding is dominant, and the style of the minor folding suggests movement of the higher tectonic levels to the north-east. The general symmetry of the formations shown on the map is the reverse of that at Schiehallion, but, although the major fold structure is asymmetric, it is not easy to ascertain whether or not it is recumbent with respect to the NW.–SE. axes. Here it is noteworthy that the axes of observable cross-folds agree with the general schistosity and foliation, and so the south-easterly plunge steepens to vertical and then becomes north-westerly in passing across the vertical belt of the regional structure.

Everywhere these major structures disappear south-eastwards, in which direction even the more widespread small-scale cross-folding also appears to be lost (see footnote p. 258). Doubtless it is significant that to the south of Schiehallion, where, as in Glen Lyon, small-scale cross-folding, though subordinate, is still discernible, the predominant Caledonoid folds are traversed by numerous sharp-pitch culminations and depressions, which give a periclinal pattern on the map. Similar culminations and depressions in other areas, often on a considerable scale (e.g. Kirkmichael and Glencoe), may well represent the effects of cross-folding, although from their broader, more symmetrical style they may bear the same relation to the typical cross-folds as do the open folds on NE.–SW. axes to the main Caledonoid recumbent folding.

This description of structural relations in the Central Highlands bears close comparison with the observations made by Kvale (1953) in a recent review of the Caledonides of Norway. Kvale shows that folding on axes transverse to the main axial direction is of local distribution, and is on a minor scale, producing translations which are generally very small compared with those associated with the main folding. In the Central Highlands, moreover, it appears that the sense of movement, as revealed by the style of the cross-folding, is in different directions in different belts. Kvale has focussed attention on linear structures, and their relation to the direction of translation. Also it is clear that, in the Scottish area, the prominent lineation, although conforming to the axial direction of the cross-folding, is, at the same time, in agreement with the direction of translation in the main fold structures. The style characteristic of the Caledonoid folding in the Moines is here interpreted as implying extreme shearing (and stretching) in NW.–SE. directions. In Norway, a stretching in the direction of the prominent lineation, i.e. transverse to the main direction of folding, is attested directly by extreme elongation of pebbles in conglomerates (Kvale, 1953, p. 56).

(c) **Relations between the two systems of folding.** In the Northern Highlands, the original view (Phemister, 1948, p. 23) that the cross-folding (and rodding) is associated with the Moine Thrust and is, therefore, distinctly later than the main folding (and metamorphism) apparently can be sustained no longer (Wilson, 1953, pp. 140–2). Indeed, Crampton (*in* Peach *et al.*, 1913a, pp. 57–8) made it clear that 'there are difficulties in explaining the Beinn Dronaig structure by a later system of vertical folding imposed upon an earlier system of overfolding'. McIntyre's interpretation of the Grantown (1951b) and Beinn Dronaig (1952) areas as determined by a single system of NW.–SE. folding, is to be regarded as of limited geometric significance, and cannot be extended to the wider area of the Central Highlands, where two systems are demonstrable on all scales. Nor can the conclusions of Coles Phillips (1951, p. 233) & Wilson (1953), be entertained in the Central Highlands, where they equate the cross-folding with that seen in the Lewisian, for here, Dalradians are involved as well as Moines, just as in Norway, formations known to be of Lower Palaeozoic age are affected by analogous movements.

Thus, it is necessary to conclude that the two systems of folds were developed during the same general epoch of folding, despite the fact that their style shows that each has been produced by compressional stresses acting in directions transverse to the fold axes. This is indeed the conclusion that was reached by Crampton (*op. cit.*, p. 58) in central Ross-shire and inferred, more recently, by Kvale (1953, pp. 61–2) in Norway. Sutton & Watson (1954), in their study of the Fannich area, also conclude that the two sets of folds were formed at the same time, but regard the NW.–SE. set merely as subsidiary flexures resulting from variations in plunge of the major N.–S. folds (p. 47).

In the area between Braemar and Schiehallion, contemporaneity of the two systems of folding is clearly to be inferred where geometric patterns are developed in the formations that cannot be resolved by imagining the folding on one set of axes to be straightened. This is true equally of the double fold illustrated by the specimen from the limestones near Braemar (Fig. 6 A), and of the major structural complex around Schiehallion. Moreover, the axes of the small-scale cross-folds always plunge in the general direction of dip which is determined by the Caledonoid folding, so that, in the Ben Vrackie area, the plunge of the cross-folds varies from south-eastwards to north-westwards, through the vertical, in a traverse from north-west to south-east. Clearly, the cross-folds cannot have been merely superimposed. Nor can they be earlier, for it is inconceivable that well-defined belts, characterised by major cross-folding could have survived the profound recumbent folding on Caledonoid axes. Nevertheless, it should be observed that in many localities a partial analysis of the structures can be made by supposing the cross-folding to be later, but this is only possible because of the very limited recumbency that is ever shown by the major cross-folds themselves.

Although it is postulated that the two systems of folds developed simultaneously, study of the detailed structures emphasises that several phases of movement were represented (see Fig. 6 B, p. 259), but the evidence appears conclusive that all the movements formed integral phases of one period of orogenesis. Moreover, although most of the structures to which attention is directed in the present account were the result of deformation of an effectively plastic medium, certain of the major slides, most of the typical thrusts, and all of the well-known tear-faults, testify to the continuance of the same directed forces into the brittle stages of deformation.

Consideration of the significance of the cross-folds, and their relation to the main Caledonoid folding, necessarily involves much that is inferential. However, the structures developed in the quartzite of Morrone, near Braemar, and the underlying belt of limestone to the north, may well throw light on the major problem. Here, at the north-east and south-west ends of the area of quartzite, the limestone shows great thickening, evidently tectonic, with dominant folds plunging south-easterly. In the quartzite, only Caledonoid folds occur. These relations suggest flow of the less competent formations at right angles to the main direction of translation of the

Caledonoid overfolds, with the development of complementary NW.–SE. folds in the zones of tectonic thickening.

On a regional scale, the dominance of cross-folding in relatively narrow belts, and its repeated variations in sense of movement, also suggests that it arose as a result of differential movement (or loading) between adjacent tectonic units, during the generally north-westerly translation of the Caledonoid recumbent folds. It is possible that the occurrence of quartzites in more or less isolated masses is a reflection of the same process. The prevalence of the cross-folding towards the Moines, and its apparent absence from the south-easterly belt of the Highlands (see footnote p. 258), may be explained by the supposition that such folding only developed at deeper tectonic levels where compression on the main Caledonoid axes could not readily find relief upwards and outwards. The predominance of lineation in a NW.–SE. direction reflects the fact that, while this direction is the *b*-axis of the cross-folds, it is at the same time the *a*-axis of the great recumbent folds. In the same way, the typical mullion structure may be explained as representing the effect of waning compressional movement, continued into the brittle phase, producing curved joint surfaces in relation to the cross-folds, just as platy jointing was produced along the original shear planes of the typical flat 'bedded' Moines.

(d) **Arcuate structures.** Although two directions of folding strongly predominate, and commonly remain distinct, on a small scale, the distribution of formations on a regional scale often display a gradual swing from one direction to the other.[1] Indeed, on this scale the folds themselves show a corresponding arcuate pattern. Thus, in the Schiehallion area, apparent synforms and antiforms show continuous variations in axial direction from NNW.–SSE. to WSW.–ENE. as they are traced southwards from Trinafour, and thence eastwards to the neighbourhood of Loch Tummel. This phenomenon was named the 'Schiehallion Twist' by Bailey & McCallien (1937, p. 106), who offered no explanation for its formation, but manifestly it originated as an accommodation structure by the simultaneous operation of locally intense cross-folding, and the main Caledonoid overfolding. That torsion played no part is shown by the fact that small-scale cross-folding is present throughout the arcuate belt, even where the trend of the formations is typically Caledonoid. Moreover, the belt of vertical dips in the Moines pursues an undeflected course from north-west of Trinafour in a south-south-easterly direction across the River Tummel. On a small scale double folds in hand specimens (Fig. 6 A) provide, in miniature, almost precise replicas of the Schiehallion structure.

A very close analogy with the Schiehallion area is provided on a still larger scale by the Bergen Arc System of Norway. Here C. F. & N-H.

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[1] It seems possible that the 'major folds about warped axes', described by Sutton & Watson (1954, p. 53) in the Fannich area, are of this character.

Kolderup (1940, pp. 133–5) conclude that the region is characterised by folding on two axial directions, the one trending about NW.–SE. and more or less normal to the NE.–SW. (Caledonoid) direction. Although no complete explanation is offered for the relations between the two systems of folding, it is concluded that the 'Caledonian' folds cannot be the later.

## 4. CONCLUDING REMARKS

The authors are keenly aware that the terms 'Caledonoid' and 'cross' folds are open to objections, but in the foregoing account they are used purely descriptively, in preference to compass directions which are apt to be confusing to the reader. Nevertheless, it seems likely that an important genetic distinction is to be inferred between the two systems of folds. The Caledonoid folds are the main folds which develop transverse to the regional orogenic stresses, whereas the cross-folds are 'accommodation' structures, resulting from the confinement of the orogenic belt in the direction of the major *b*-axis. In this sense they arise from complementary stresses produced in the orogenic belt during deformation, and do not reflect the direction of forces applied externally in the development of the orogenic belt as a whole.

Since the above account was written, other work has provided important additional information as to the relations between the two systems of folding. Reynolds & Holmes (1954, p. 417) have shown that in the Malin Head area of Donegal, Caledonoid folding has been superimposed on an older set of NW.–SE. folds, while Mary C. Vogt (Ph.D. thesis, University of Glasgow, 1954) has recognised two axial directions of folds in the Ballachulish area. Here, also, the two directions are shown by the orientation of quartz in petrofabric diagrams. In Clough's classic region of Cowal, Argyllshire, the present writers have found that episodes of cross-folding have alternated with episodes of Caledonoid folding in the development of the structures of the Cowal anticline. Only where the rocks show the lowest grades of regional metamorphism can all stages in the movement history be clearly discerned. The implication is that, in the more crystalline rocks to the north and north-east, only the later phases of movement can be recognised, but that folding in the two directions has occurred repeatedly in the regions showing complex structures. Thus, in particular localities it is possible to find examples of cross-folding either ante-dating or post-dating Caledonoid folding, or yet again examples in which the structures appear to have developed simultaneously.

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## DISCUSSION

DR. J. SUTTON congratulated the authors on a paper which he had found most illuminating. The double folding described in the paper strongly recalled the double folding of the Moines in the North-West Highlands. In both areas the cross-folds were often monoclinal, or at least markedly asymmetric, and had the effect of producing regional culminations or depressions in the main or Caledonoid folds. The arguments employed by the authors to show that the folds were, broadly speaking, contemporaneous were equally applicable in the Moine structures known to the speaker.

Dr. Sutton enquired whether the authors had studied the Moines farther northwest than the ground covered by the paper. If so, what tectonic styles had they found. In north-east Scotland, on the coast of the Moray Firth, the Dalradian structures appeared to be divisible into three great groups. In an upper zone, simple folding not accompanied by intense deformation of the rocks was the rule. Below this came a zone of intense distortion and disruption. These two zones seemed analogous to what had been described by Dr. King and Mr. Rast above and below the Loch Tay Limestone. In the north-east, a third zone in which simple structures were formed underlay the complex zone, and the lowest Dalradian groups on the coast (Findlater Flags to Cullen Quartzite) showed no signs of having been subjected to intense penetrative movements.

This led the speaker to suggest the features of this third zone might be found elsewhere, and that the complexities found by the authors in the uppermost Moines might not continue in lower horizons.

There appeared to be greater recumbent structures in the uppermost Dalradian than in any underlying beds. It seemed possible that the intensely deformed zone separated regions of the Caledonian mountains that had been deformed in quite different fashions and that in a broad sense it acted as a zone of decollement, the structures above which bore no close relation to those below.

DR. GILBERT WILSON said that he considered this paper a most valuable contribution to our knowledge of Scottish geology, and the authors were to be congratulated. The manner in which they had demonstrated that the development of two sets of folding at right-angles—one trending north-east, and the other trending south-east—in the Dalradian and Central Highland Granulites were contemporaneous, is a great advance in the elucidation of the tectonics of the Grampians. He looked forward to the publication of this, and of the more detailed papers which were promised.

The speaker was, however, not yet convinced that such a principle of penecontemporaneous development of double folding could be applied throughout the Highlands. In north Sutherland he had so far observed only easterly or south-easterly trending folds, many of them being recumbent. The only structures having a north-easterly (or Caledonoid) trend were thrusts. These latter cut the folds, broke down the metamorphism, and so appeared to be late in the local tectonic history. In other details some of the Moinian structures in Sutherland corresponded closely with those described that evening. For instance, recognisable fold-hinges commonly graded into flaggy Moines on the isoclinal fold-limbs; but where weathering had etched out the stratification in these flaggy types, the bedding appeared as tight flat folds, comparable to some of the examples shown on the screen. Siliceous schists with large muscovite folii had also been noted; and these the speaker—like the authors—had mapped as tectonic schists. The rocks, however, were not so rich in mica as the specimens exhibited.

The region described by Dr. King and Mr. Rast is one of intense sliding or thrust tectonics, as is the Bergsdalen Quadrangle in Norway (A. Kvale, 1948, Petrologic and Structural Studies in the Bergsdalen Quadrangle, Part II, *Bergens Museum Arbok*, 1946–7, *Naturv. rekke*, 1). In both areas, folding and lineation parallel to the direction of regional tectonic transport are strongly developed. Similar structures are now being found in the vicinity of the Moine Thrust. One cannot but wonder whether there may not be some mechanical relationship between intense, penetrative thrust-movements, such as those described by the authors, and the development of cross-folding.

DR. E. H. T. WHITTEN appreciated the extreme lucidity of Dr. King's paper, and said that, in view of what had been described, some of his own recent observations in the Monadhliath might be of interest. The area examined by the speaker was of particular interest, being immediately west of the maligned 'Grantown area' of McIntyre, and to the north of the Schichallion country. Two distinct directions of folding had been detected in adjacent rocks. Westwards to Newtonmore broadly south-east-trending folds occur, with long flat members and short steep limbs, analogous in style to Dr. King's 'cross folds'. Farther west, south-west-trending folds occur. There is little apparent evidence of overprinting, which makes it likely that the folds were of pene-contemporaneous origin, and thus that in outline there is a correspondence with Dr. King and Mr. Rast's findings to the south.

The comments upon the style detected in the Moine rocks north and east of Schichallion had also been of particular interest because of the speaker's observations south of the Spey. All exposures show prominent gently-dipping jointing, which has been recorded as dip on H.M. Geological Survey maps. The state of weathering, and quartzitic nature of the rock, causes the bedding to be invisible in the majority of cases. However, careful examination of those rare sections in which bedding is to be seen reveals tightly-repeated folding which must be ubiquitous in that area, though extremely difficult to observe.

J. R. HARPUM said that although the previous contributors to the discussion had confined their remarks to the Scottish Highlands, it was clear that the paper just read to the Association was of importance to all geologists working on crystalline rocks. It was of particular interest to those engaged in mapping in the vast pre-Cambrian terrains and shields such as are found in Canada and eastern Africa. Although many features mentioned in the paper might receive comment, the speaker wished to consider two aspects of it that had a bearing on the geology of Tanganyika.

The first of these concerned the 'tectonic schists' found in association with the slides in the Dalradians. The term 'tectonic schists' was a very useful and apt description of many schistose rocks in Tanganyika, which were originally recorded, mapped and even correlated as stratigraphical units. Recent work has shown, however, that, in many cases, these rocks are 'tectonic schists' in the sense employed by the authors. They are without stratigraphical significance and frequently include rocks of widely differing ages in close association. It has been found in Tanganyika that such rocks are frequently indicative of the superposition of orogenic belts, and are often permeated. The permeation was typically a potash metasomatism with the production of sericite or muscovite and, in more advanced cases of potash feldspar porphyroblasts. The speaker enquired whether the authors had found evidence of a similar metasomatic activity in the 'tectonic schists' of the slides in the Scottish Highlands.

The second aspect the speaker wished to mention concerned the 'flagginess' of the Moines, which the authors had interpreted as a tectonic rather than as a sedimentary feature. The Moines are a relatively low-grade metamorphic assemblage, so that the conditions for the preservation in them of minor structures indicative of major recumbent structures would be fairly good. In much of the eastern part of Tanganyika, there were vast areas of very high-grade rocks of the granulite facies which showed fairly low regional dips and remarkable uniformity of banding over great distances. This banding has hitherto been interpreted as true bedding, but this paper suggests that it may be nothing of the sort. It is difficult to imagine conditions giving rise to such a high-grade regional metamorphism which would produce a series of rocks with such gentle and uniform dips. In a personal discussion with the speaker, Mr. Rast had suggested that this banding was essentially a tectonic feature. In view of the high grade of metamorphism in eastern Tanganyika, structures similar to those seen by the authors in the Moines may there have been completely dispersed, and the true significance of the banding difficult to demonstrate.

Finally the speaker thanked the authors for a paper so useful to those interpreting structures in pre-Cambrian and other metamorphic terrains.

DR. B. C. KING, replying on behalf of the authors, said they were very gratified by the favourable reception of the paper and by the interesting and fruitful discussion it had evoked.

Regarding Dr. Sutton's comments, the authors, in view of their as yet limited observations on the Moines farther to the north-west, were not at present qualified to express opinions regarding the structures of the Moines on a regional scale. Moreover, the findings of all workers on the Moines, both past and present, serve to underline the necessity for caution in making assertions regarding the large-scale structures. The present authors would emphasise the extreme difficulty in determining the large-scale pattern, consequent upon the lithological uniformity of the Moines, even with the most careful mapping, for this may reveal no more than a later superimposed folding. Small-scale folding eludes detection except in the most favourable exposures, such as coastal sections, while the preservation, locally, of sedimentational structures could prove quite misleading as to the extent of deformation on a larger scale.

It is appropriate to recall in this connection that the widely different interpretations of the so-called 'Lewisian inliers' of Morar and the Fannich Forest areas, recently re-examined by Professor Kennedy and by Drs. Sutton and Watson, respectively, involve correspondingly divergent views on the complexity of the fundamental structures in the Moines. Again, it is virtually certain that, but for the presence of lithologically distinctive formations in the Dalradians of the Ballachulish area, the great recumbent nappes inferred many years ago by Sir Edward Bailey would have remained quite unsuspected. Moreover, if these are the structures in the Dalradians, what are the structures in the Moines with which the Dalradians are in contact, from Glen Orchy to Loch Linnhe?

The authors were not clear as to what Dr. Wilson implied by his observations regarding the sequence of tectonic events in north Sutherland. If it is suggested that the *only* Caledonoid structures are late thrusts, with associated retro-metamorphism, which post-date the easterly or south-easterly cross-folds, then the Moines of the region must be regarded as a continuous sequence of immense thickness, rising towards the east or south-east. The alternative was the orthodox view that the distribution of mappable formations showing NNE.–SSW.-trending outcrops implied some repetition, at least by large-scale isoclinal folds on Caledonoid axes.

Regarding the contemporaneity of the two directions of folding, more recent work by the authors in Cowal shows very clearly the complexity of this problem. In Cowal no less than four episodes of folding can be established with certainty, both cross- and Caledonoid directions being represented, so that on a small scale either direction may locally appear to be the later. Although contemporaneity may sometimes appear to be the inescapable conclusion regarding small-scale structures, as also observed by Dr. Whitten, it is especially on the large scale that the impossibility of elucidating the geometry of the major pattern by supposing one direction of folding to be wholly earlier or later leads to the conclusion that the two directions operated broadly simultaneously.

It appears, too, from this more recent work that cross-folding, at least on a small scale, is much more widespread in the Highlands than the authors originally supposed. It may indeed prove to be ubiquitous. In any event its abundant development in the southern parts of the Highlands suggests that it bears no direct relation to the intense thrust movements, of which the Moine Thrust is the most spectacular, as suggested by Dr. Wilson.

Mr. Harpum's observations are of especial interest in that they direct attention to the fact that the results of structural studies in the Scottish Highlands are of world-wide application, and of especial concern in the great Pre-Cambrian terrains. It may be noted that a tectonic origin for the banding in gneisses in an area in Nigeria was postulated some years ago by one of the authors (B. C. King & A. M. J. de Swardt. 1949. The Osi Area of Nigeria. *Bull Geol. Surv. Nigeria* No. 20, 6–7).

# The Correlation of the Pliocene and Pleistocene Marine Beds of Britain and the Mediterranean

by D. F. W. BADEN-POWELL

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**ABSTRACT:** The marine mollusca of the Pliocene and Pleistocene beds of Britain and parts of the Mediterranean region are compared. Correlation between the two areas is based partly on the evolution in certain groups of mollusca, and partly on a reconstruction of the geological history of the Gulf Stream Drift and of the shifting of the climatic belts, as shown by the distribution of some of the fossils. The future use of these correlations is discussed, and the palaeontological evidence is shown to favour the theory of past eustatic changes of ocean level, thereby confirming the hypothesis of Glacial Control, to some extent.

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## 1. INTRODUCTION

TWO EVENTS which occurred in Pliocene and Pleistocene times have impressed themselves most strongly on the minds of geologists: great climatic changes, and their accompanying fluctuations of sea-level. The hypothesis of Glacial Control which has been built up during the last few decades, to connect these two events, suggests that the world-wide height of sea-level is controlled by fluctuations in the ice-caps of the earth. This hypothesis has been accepted widely, but it is not always realised that it depends on the idea that eustatic changes of sea-level have taken place, the proof of which depends on the accurate correlation of raised beach deposits, and other marine beds, over great distances. Many years ago this point was emphasised by Daly (1920), and at about the same time Deperet (1918 and 1920) tried to correlate some British raised beaches with the classical series in the Mediterranean, depending chiefly on the criterion of height above sea-level. Although Deperet was partly successful in this attempt, certain palaeontological anomalies were found during this work which he did not explain. Therefore, an accurate correlation of Pliocene and Pleistocene marine beds must be worked out before the hypothesis of Glacial Control can be accepted, and this correlation cannot rely on measurement of heights alone, because these are known to vary in certain areas; a palaeontological method is essential, to surmount this difficulty. Other uses which can be made of such marine correlations are discussed at the end of this paper.

The correlations here proposed have been summarised elsewhere (Baden-Powell, 1953): they are restricted to western Europe. In fact, the main object is to find out how the marine beds of Britain and Ireland fit in with the classical series in the Mediterranean. Although foraminifera, and other fossils, have their importance in work of this kind, the marine mollusca have been found to be the most useful in the present investigation, and are the subject of the present discussion. The marine sequence was worked out for the Mediterranean mainly by Gignoux (1913) and Deperet (1918), but it has been modified somewhat by later workers. The general succession is as follows:

MARINE SUCCESSION IN THE MEDITERRANEAN AREA

| | | |
|---|---|---|
| HOLOCENE | Flandrian | Fauna slightly warmer than today; no extinct shells |
| PLEISTOCENE | Monastirian | Return of warm fauna; a few extinct shells survived |
| | Tyrrhenian | |
| | Sicilian | Cold immigrants in the Mediterranean; fewer extinct shells than in the Astian |
| | Calabrian | |
| PLIOCENE | Astian | Warm fauna with many extinct species |

**Notes on the Mediterranean Sequence.** Sometimes the **Calabrian** is divided into lower and upper portions, but whereas Gignoux (1913) thought that the cold indicators were more common in the Upper Calabrian, some Italian geologists now claim that the cold indicators are absent from the Upper Calabrian, suggesting an amelioration of climate between the Calabrian and the Sicilian. The name **Emilian** has been given to this Upper Calabrian by Ruggieri (1949, p. 34) and by Ruggieri & Selli (1950, p. 90), but as yet no such marine stage has been recognised in Britain, unless it is represented by the Cromer Forest Bed. A **Milazzian** stage was originally placed between the Sicilian and the Tyrrhenian by Deperet, but Italian geologists now regard this as a regressive phase of the Sicilian; it seems to have no British equivalent which can be recognised palaeontologically, and is omitted from the above list, therefore. The fauna of Deperet's **Monastirian** is similar to that of the Tyrrhenian, in the Mediterranean area, and the two have been confused at some sites. In recent years there has been some doubt about the separate existence of the Monastirian. To get over this difficulty the name **Ouljian** has been proposed by Gigoux (1949) for a Post-Tyrrhenian beach in Morocco. The name Monastirian will be retained in the present paper, owing to its long usage. Finally, Dubois' name **Flandrian** (Dubois, 1924) is used by some geologists for the transgression which occurred during the climatic optimum of the Holocene, but this name has also been employed for part of the Eocene and is thus preoccupied strictly speaking.

The British succession, mainly the work of Wood and Harmer (with additions by the present author), can be listed as follows:

MARINE SUCCESSION IN BRITAIN

| | | |
|---|---|---|
| HOLOCENE | Raised Beaches | Fauna slightly warmer than today; no extinct species |
| GLACIAL SERIES | March Gravels and Kelsey Hill Beds | Fewer warm forms than in Corton Beds; very rare extinct shells |
| | Corton Beds | Return of warm fauna after Bridlington Crag; several extinct species are common |
| | Bridlington Crag | Maximum cold fauna: several extinct species |
| EAST ANGLIAN CRAGS | Icenian | More cold and fewer extinct species than in the Red Crag |
| | Red | Increase of cold fauna; fewer extinct species than in the Coralline Crag |
| | Coralline | Mainly warm fauna with many extinct species |

**Notes on the British Sequence.** The characters of the fauna of the Coralline, Red and Icenian Crags were described in monographs by Wood (1848–82) and Harmer (1914–26). They include the sudden appearance of certain species at definite horizons, in addition to the well-known deterioration of climate which took place from bottom to top. The term **Bridlington Crag** has been used for derived material in the lowest glacial tills of the Holderness coast of Yorkshire, formed in an intensely arctic climate. Originally it was placed by Wood in his 'Upper Glacial' formation (1872), but later was transferred by him to his 'Lower Glacial' formation (Wood, 1882). The name **Corton Beds** was given to Wood's 'Middle Glacial Sands', so as to define this marine horizon more sharply (Reid Moir & Baden-Powell, 1938) and later the nature of the fauna was outlined by the author (Baden-Powell, 1950). Distinctive features of the latter are the return of a warm fauna, after the cool period represented by the Cromer Till and the Bridlington Crag, and by the appearance of many species unknown in the earlier deposits. By several geologists (Harkness, 1869; Harmer, 1872), this horizon has been recognised as palaeontologically distinct from the **March Gravels** of Cambridgeshire, the March Gravels having fewer extinct species and a colder climate than the Corton Beds.

It must be emphasised here that, in the present paper, the attempt to correlate this British series of marine deposits with those of the Mediterranean is made by *palaeontological* means: the heights above present sea-level which may have been reached during various stages in the two areas cannot be used, by themselves, as criteria of age. At the start of this work, comprehensive lists were made of the marine mollusca from each zone in the two areas, and the species and varieties common to both were compared. The data have been verified as far as possible, both in the field and in various collections in this country and abroad, reliance being placed mainly on the forms which are most abundant. Space does not permit publication of the complete lists here, but the more important species and varieties are named in subsequent parts of this paper.

The fossil molluscan fauna of the two areas has been found to differ from that of the present day in two main respects: (a) the presence of extinct species together with the lack of certain 'modern' forms, and (b) the climatic changes shown by warm and cold indicators in certain areas. These two ways of zoning can be employed independently, and each used as a check on the other.

## 2. DATING BY EVOLUTION OF SPECIES

**Dates of extinction:** For a long time it has been realised that the earlier marine deposits of the Pliocene–Pleistocene series contain more extinct species than the later beds, and Lyell's subdivisions of the Tertiary were, in fact, based on this progressive extinction of certain forms. Many geologists, from Lyell to the present day, have tried to express the number of extinct forms at any one horizon as percentages of the whole known fauna; during the present investigations I have not tried to represent the extinct forms as percentages, because this method depends largely on the total number of species found in any zone and is affected seriously by the divergence of opinion among experts on identification, especially of the rarer forms.

In his classical description of the marine deposits of southern Italy and Sicily, Gignoux (1913) stressed the fact that the Astian beds contain more extinct forms than the later Calabrian and Sicilian formations, and that the Tyrrhenian and Monastirian beaches have very few extinct shells. A similar progressive extinction is found in the British area as the succession is traced upwards from the Coralline Crag through the Red Crag and Icenian to shell-beds in the Glacial Series, as is well known from the work of many geologists, including Wood (1848–82), Harmer (1914–25) and Bell (1893). The course of extinction is so similar in the two areas that the contemporaneity of the two sequences is obvious; but it is not easy to correlate individual stages by the extinction of certain species because there is reason to believe that some shells lingered on, as relicts in the open Atlantic, after they had died out in the Mediterranean. However, the older part of the Coralline Crag (the Gedgravian) contains so many species which did not survive that zone, and which also became extinct during the Astian, that it seems safe to consider the Gedgravian as of Astian date. The Boytonian, or upper part of the Coralline Crag, may also represent the top of the Astian, though it will be shown in the description of the evolution of *Nassa* that there is something to be said for assigning the Boytonian to the base of the Calabrian.

At this point a short digression must be made from these long-distance correlations to point out that the order of extinction of certain species has been found to be important in distinguishing some of the later stages in the British sequence. In earliest work on the marine succession by the author, in which the principle of 'climatic equivalent' was defined (Baden-Powell, 1927), he was so absorbed in the climatic succession that he did not appreciate the importance of the order of extinction of certain species; during the present investigation, however, he has found that the dates of extinction of some of the shells have helped in the subdivision of the Post-Icenian deposits. An analysis of the faunal lists shows that between a lower limit, represented by the Crags with their numerous extinct shells, and an upper limit, consisting of the Holocene beds which have been defined as having no extinct species (Baden-Powell, 1937), the shell-beds in the Glacial Series are intermediate, containing certain extinct species which have survived from the Crag. These last are not derivative, however, because many of the common Crag forms are missing, having become extinct by the end of the Icenian, or even earlier.

Analysis of the British faunal lists also shows that the progressive extinction took place in at least two stages during glacial times. The earlier of these stages is typified by the Corton Beds fauna, and the later stage with the assemblage found in the March Gravels of Cambridgeshire and the Kelsey Hill Beds of Yorkshire. A probable third stage, represented by marine material in the Cromer Till and the so-called Bridlington Crag, may be equally important, coming stratigraphically between the top of the Icenian (Weybourne Crag) and the Cortonian, but its fauna needs further investigation.

The most important of the Crag survivals in the Corton type of fauna (Baden-Powell, 1950, pp. 196–7) are the extinct species *Nucula cobboldiae* Sowerby, *Tellina obliqua* Sowerby, *Purpura incrassata* Sowerby and *Nassa reticosa* Sowerby. This assemblage is found in the Corton Beds of East Anglia, and some of these species have also been recorded from the drift of Holderness (Yorkshire), from Aberdeenshire, the Isle of Man and the Wexford Gravels of south-east Ireland. In several places the marine material may be glacially transported, but its fauna remains recognisable. The marine clay at Selsey (Sussex) also contains a number of extinct species, but these are not identical with those in the Cortonian. This Sussex clay has been correlated with a high-level raised beach not far away. Space does not allow of full reference to these localities.

The March Gravel–Kelsey Hill type of fauna is much more widespread than the Cortonian and is stratigraphically younger than that deposit; it differs from the Cortonian in containing an almost entirely modern fauna, and such forms as *Nucula cobboldiae* and *Nassa reticosa* have become extinct by this stage. *Tellina obliqua* is almost the only extinct shell known from the March–Kelsey Hill horizon and is so rare that in a hundred years of research only two valves have ever been found—one in Lincolnshire and the other in Cambridgeshire. From the point of view of extinct shells this zone is intermediate between the Cortonian and the Holocene. It is represented by the Burtle Beds of Somerset, most of the raised beaches of southern England (as at Tor Bay and Portland); the March Gravel and Nar Valley Clay of the Fenland; the Kelsey Hill Beds of Yorkshire; at least part of the Clyde Beds of Scotland, including such localities as Clava and King Edward; and much derived material in eastern Ireland (especially at Ballyrudder), Wales, Lancashire, Cheshire and Shropshire (including the high-level drift of Moel Tryfaen, Gloppa and Macclesfield). The difference between all these deposits, on the one hand, and the Cortonian type, on the other, is most marked in respect of the details of their faunas. Although the general absence of extinct shells in the later group of beds is a negative character, once the two types of bed have been separated in this way they are found also to have climatic characters of their own which are described below. The extinct form of *Tapes senescens* Cocconi, which has been found in the Eem horizon in Holland and Germany and in the Monastirian of the Mediterranean area, might be expected in the March Gravel horizon of Britain, but has not yet been recorded.

**Dates of arrival of new species.** It is now necessary to return to the wider question of British–Mediterranean correlations. An analysis of the fauna of the Mediterranean stages shows that certain species occur only from particular horizons upwards in the succession, being unknown in earlier deposits. The same is generally true of the British area, where a number of common living species are unknown in the Crags. It is possible that imperfections of the geological record, or differences of facies, are responsible for some of these examples, but a comparison of the dates of arrival of certain shells in the two areas shows that every case cannot be explained in terms of these factors.

In the lists compiled by the author there are many species which make their first appearance in the Mediterranean area during the Calabrian, being unknown in the Astian or earlier beds. Some of these Calabrian arrivals are well-known Coralline Crag shells in the British area, but this fact cannot be taken as a necessary proof of the Calabrian age of the Coralline Crag, because some of the Calabrian arrivals, such as *Cyprina islandica* Linn., *Tapes virgineus* Linn. and *Mya truncata* Linn. were 'cold immigrants' in the Mediterranean area; in other words, these forms could live in British waters at the time of the Coralline Crag but the Mediterranean of Astian times was too warm for them.

On the other hand, there is an important group of Astian and Calabrian arrivals in the Mediterranean area which did not reach Britain until the Cortonian. These include *Cardium tuberculatum* Linn., *Cardium exiguum* Gmelin, *Venus verrucosa* Linn., *Venus gallina* Linn., *Tapes decussatus* (Linn.) and *Gibbula magus* (Linn.). These shells are considered to be part of the Mediterranean fauna which appeared in that area during the Astian or Calabrian, but which, for some unknown reason, only reached Britain as warm immigrants in Cortonian times. It is most significant that many of these immigrants also reached Holland at a late Pleistocene date (Van der Vlerk & Florschütz, 1953, pp. 25–9). Further, the Astian shell *Skenea planorbis* (Fabricius) and the Calabrian arrival *Tellina tenuis* da Costa seem to have arrived in Britain only at the March Gravels–Kelsey Hill stage, and there are even examples among rarer species of Astian and Calabrian immigrants which did not reach Britain until the Holocene.

These facts seem to be related to the effects of climatic factors on past distribution and cannot be used for correlation between Britain and the Mediterranean. However, in addition to the dates of arrival mentioned so far, there is a significant number of species which were Calabrian arrivals in the Mediterranean area and Red Crag arrivals in Britain. The most important of these are given in the following list, and are taken as evidence for the Calabrian age of the Red Crag.

### LIST OF CALABRIAN–RED CRAG ARRIVALS

*Modiola barbata* (Linn.)
*Modiola modiolus* (Linn.)
*Nucula tenuis* (Montagu)
*Venus fasciata* (da Costa)
*Spisula solida* (Linn.)
*Turritella pliorecens* Monterosato
*Nassa pygmaea* Lamarck
*Buccinum humphreysianum* Bennett
*Trophon barvicensis* (Johnston)
*Neptunea contraria* (Linn.)
*Bela rufa* (Montagu)
*Raphitoma laevigata* Philippi
*Trivia sphaericulata* Lamarck

*Turritella pliorecens* is one of the most important shells in this list, and may almost be counted as a 'zonal fossil'.

Having reached the conclusion that the Red Crag appears to be dated as Calabrian, it is important to find out whether any Post-Calabrian arrivals have their earliest record in this country later than the Red Crag. *Chlamys islandica* (Müller) has been recorded by Gignoux (1913, p. 373 and pl. X) from the Sicilian of the Mediterranean, and it may be significant that this species is unknown in the British Crag and makes its first appearance here, in the 'Bridlington Crag' of Holderness, indicating that at least part of that glacially derived material may be the British representative of the Sicilian. As there is some evidence that the till which contains *Chlamys islandica* in

Holderness can be correlated with part of the Cromer Till in Norfolk, it is possible that the Cromer Forest Bed is Pre-Sicilian, as it underlies the Cromer Tills.

If this enquiry is extended further, in an attempt to identify Tyrrhenian arrivals with newcomers in the Cortonian, *Nassa reticulata* (Linn.) is the only species discovered so far which is a Tyrrhenian arrival first appearing in Britain during the Cortonian. It is true that this species has been recorded from the Astian by Bellardi (1883, p. 263 and pl. III, fig. 7) and from the Calabrian by Cerulli-Irelli (1911, pl. XXII, figs. 29–30), but these illustrations show shells which are more involute and have fewer vertical ribs than living examples of *Nassa reticulata*, and seem to belong to an extinct ancestor allied to the living *Nassa nitida* Jeffreys. If this identification is correct, we have some evidence of the Tyrrhenian age of the Corton Beds, a correlation supported by climatic considerations which are discussed later in the present paper. It is further confirmed by the fact that the existing shell *Turritella communis* Risso becomes common for the first time during the Tyrrhenian and the Cortonian.

**Phylogenetic evolution in the genus Turritella.** It is now obvious that extinction of old forms, and arrivals of new species, can be taken together as examples of phylogenetic evolution and can be used for zoning. As the same species and varieties of *Turritella* are found fossil both in Britain and in the Mediterranean deposits, they are extremely important. Harmer (1914–19, p. 441) considered that some forms of *Turritella* have a zonal significance in the British sequence, and he showed that *Turritella tricarinata* (Brocchi) is the common form in the Coralline Crag and that *Turritella communis* Risso does not occur frequently until one reaches the Glacial Series. Gignoux (1913, p. 552) considered that among the Mediterranean beds *T. tricarinata* is the typical Astian form and that *T. communis* only becomes dominant after the Sicilian. He proved that an intermediate species, or variety, *pliorecens* Monterosato is common in the Calabrian and Sicilian deposits, and claimed that *T. communis* is descended from the extinct shell *T. tricarinata* by way of the intermediate *T. pliorecens*. Not only does the size of the shell increase from *T. tricarinata* to *T. communis*, but the ornament of three spiral ridges seen in *T. tricarinata* acquires subordinate intermediate ribs in *T. pliorecens* which strengthen in *T. communis* until they are as strong as the original three primary ribs and make seven or more ribs of equal size. Gignoux also noted that the *tricarinata* and *pliorecens* forms of ornament can be recognised on the early whorls of the modern individuals of *T. communis*. A statistical method of using these facts has been devised by Bondi & Sandrucci (1949, pp. 5–7 and pl. I, figs. 2–4), which confirms the dominance of *T. pliorecens* during the Calabrian. The author's collection from the Red Crag shows that *T. pliorecens* is the dominant form up to and including the Butleyan Zone.

This study of evolution of *Turritella* proves that the Red Crag is dated as Calabrian. As already stated, *T. communis* takes the place of *T. pliorecens* in the Glacial Series in Britain.

**Evolution in the genus Nassa.** The forms produced by evolution in *Turritella* are particularly useful for correlation between Britain and the Mediterranean because the same species and varieties are found fossil in both areas. Unfortunately a similar use of *Nassa* is more restricted because the common form in the English Crag, *Nassa reticosa* Sowerby, is almost unknown in the Mediterranean deposits, and the common Mediterranean species such as *Nassa musiva* (Brocchi) and *Nassa clathrata* (Born) are not often found in Britain. In spite of this difficulty, however, it is possible to get some data on the evolution of certain groups common to the two areas.

The first group which can be used is that including *N. musiva* and *N. reticulata* (Linn.). Gignoux (1913, p. 508) considered that although the Astian form *N. musiva* survived until the Upper Calabrian, or even the Sicilian, before becoming extinct, it gave rise to a branch called *N. crassesculpta* Brugnone which is particularly developed during the Calabrian. *N. lamellilabra* Nyst is the name used by Harmer for the Boyton Crag shells which seem identical with the Calabrian form *N. crassesculpta*, confirming the Calabrian age of the bed at Boyton (presumably the very base of the Calabrian). Gignoux believed that the recent form *N. reticulata* belongs to the *N. musiva*-Group, and as we have already seen, this form does not seem to have developed fully until the Tyrrhenian–Cortonian stage. The *N. clathrata*-Group also produces some evidence for dating. Gignoux has shown that his variety *N. ficaratiensis* flourished during the Calabrian and Sicilian, and he believed that it was descended from the extinct shell *N. clathrata*. The Coralline Crag and Red Crag form of this group shown by Harmer (Plate XXXIII) is identical with *N. ficaratiensis* and Harmer himself expressed this as his opinion (p. 317). The author has also found an example of *N. ficaratiensis* in the Newbournian Zone of the Red Crag. Finally, two closely-related living species, *N. incrassata* (Ström) and *N. pygmaea* (Lamarck), began to diverge from an ancestral form during the Calabrian and the Red Crag respectively.

The results of this study of the evolution of certain forms of *Nassa* show that some of the Coralline Crag may represent the top of the Astian or the base of the Calabrian; that the main Red Crag deposits are of Calabrian age; and that the Corton Beds are of Tyrrhenian date. These results agree with those obtained by a study of *Turritella*. There is some evidence that the Calabrian age of the Red Crag will be confirmed by an investigation of the ancestry of other shells in the list of Calabrian–Red Crag arrivals, including *Venus fasciata* da Costa and *Spisula solida* (Linn.), but a large collection of specimens must be examined before this can be established.

## 3. CLIMATIC BELTS REPRESENTED BY MOLLUSCA

Fortunately, the study of the evolution of certain species is not the only way in which the British deposits can be dated in terms of the classical Mediterranean series; it is possible to check this method by studying the past changes of climate which can be inferred from the distribution of some of the fossils. It is well known that many of the common shells in Pliocene and Pleistocene marine beds belong to species which are still living near the fossil sites in both the British and the Mediterranean regions. This fact proves that climatic belts similar to those of today existed during Pliocene and Pleistocene times, but it is also possible to show that the position of the climatic belts has been changing constantly. Nearly a century ago, James Smith (1862) recognised that a cold climate is indicated by the Clyde Beds in Scotland, as some of the fossils can be identified with species now living near Scandinavia. Later, Praeger's work (1898) established that the climate was warmer than it is today during the formation of the Holocene beds of Northern Ireland. Researches of this type were advanced by Brøgger, who proved that the Yoldia Clay, formed during a cold period, was followed by the Littorina Beach with warm indicators, and both this work and the researches on the Mediterranean deposits have proved that it is possible to build up a climatic sequence in terms of the mollusca found in particular regions. However, great caution must be exercised in trying to correlate one region with another by climatic sequence alone.

In his memoir on Southern Italy and Sicily, Gignoux (1913) showed how a study of the fossil mollusca proved that the warm climate of the Astian period gave place to increasingly cold conditions during the Calabrian and Sicilian, and that a warmer climate returned during the deposition of the raised beaches which were later described by Deperet as Tyrrhenian and Monastirian. Gignoux explained these facts by assuming the entry into the Mediterranean of warm or cold 'immigrants' from the Atlantic.

It is most significant that an exactly similar climatic sequence is known in Britain, where the warm fauna of the Coralline Crag gradually gave place to the incoming colder assemblages of the Red Crag, Icenian and the shell-beds in the oldest glacial deposits. These events were followed by a partial return of a warmer fauna during the formation of the Corton Beds of East Anglia, with its associated deposits in Yorkshire, Aberdeenshire, the Isle of Man, Wexford and Sussex. The climatic sequence in Britain, as represented by the successive marine assemblages, is so similar to that in the Mediterranean area that this method of correlation strongly supports the one already worked out by studying the evolution of certain mollusca. The latter indicates especially that the Red Crag is Calabrian and the Corton Beds are Tyrrhenian, but a detailed examination shows that cold indicators appeared in the Coralline Crag to a greater extent than in the

Astian. To explain this anomaly it is necessary to try to reconstruct in detail the past distribution of the climatic belts involved. It is interesting to note that, many years ago, Morley Davies (1934, p. 213) expressed the opinion that cold conditions seem to have affected the British seas earlier than they affected the Mediterranean.

## 4. CORRELATION IN TERMS OF TEMPERATURE GRADIENT

Deperet's work (1918) on the cold climate of the Sicilian beaches, as compared with the warmer climate of the Tyrrhenian and Monastirian stages, was fresh in the author's mind when he started work on the British climatic sequence (Baden-Powell, 1927), but he realised that there were contradictions in the evidence which were difficult to explain. When Deperet had tried to correlate certain British raised beaches with those of the Mediterranean (1918, pp. 979–84 and 1920, pp. 159–63 and 213–18), he based his work on the heights of the deposits as well as upon their fauna, and considered the '100-ft. beach' of Scotland, with its supposedly cold shells, to be contemporaneous with the warm Tyrrhenian; he also pointed out that the so-called 100-ft. beach of Sussex was associated with a warm fauna. As the author's early work did not remove these difficulties, he determined to investigate critical areas in detail with a view to solving this problem. This work has led to the unexpected results here described.

As a result of the study of the Portland raised beach (Baden-Powell, 1930) and of the fossils in the March Gravels (Baden-Powell, 1934), both now considered as Monastirian beaches, the author's original opinion was that the cold indicators in these two deposits were especially important, but the discovery of the warm indicator *Astralium rugosum* (Linn.) in the Monastirian beach at the Belle Hougue Cave, Jersey (Zeuner, 1946), helped to convince him that there is a mixture of warm and cold indicators in the Monastirian beaches of the English Channel area. This mixture has also been reported from the Burtle Beds of Somerset, and from the raised beaches of Tor Bay and Sangatte, near Calais. The mixture of warm indicators, such as *Cytherea chione* (Linn.), with cold indicators, such as *Astarte borealis* Chemnitz, is also found in the Kelsey Hill Beds of Yorkshire and in the derived material in the Irish Sea Drift of Wales, Lancashire, Cheshire and Shropshire, which has been considered Monastirian because of the lack of extinct species. It is only when the Clyde Beds of Scotland are reached that the cold indicators are found without warm ones. When it is remembered that the climate of Monastirian time in the Mediterranean was rather warm, the distribution of the critical indicators as a whole suggests exaggerated cold conditions in the north, and exaggerated warm conditions in the south, compared with those of today.

On coming to investigate some of the older British deposits, the author found that in Northern Lewis (Baden-Powell, 1938) *Sipho jeffreysianum* (Fisher), not known living north of Cornwall, and *Trophon clathratus* (Linn.), not known living south of Norway, undoubtedly occurred in fossil form in the same interglacial marine layer. This kind of mixture is also well known from the Corton Beds and their associated deposits (Baden-Powell, 1950) and appears to extend northward to some of the Tyrrhenian shell-beds of Aberdeenshire, though further work is needed in the north to distinguish between the Sicilian and the Tyrrhenian faunas. Deperet has proved that the climate indicated by the Tyrrhenian fauna of the Mediterranean was warmer than that of Monastirian time, and again the general distribution of the warm and cold indicators during the Tyrrhenian suggests determination by latitude. It is important to remember that although the warm immigrants are so characteristic of the Tyrrhenian beaches of the Mediterranean, Deperet (1918, p. 484) also named some cold indicators mixed with the warm ones.

The distribution of warm and cold indicators may be summarised as follows:

(a) The Monastirian beds in England and the Mediterranean have a mixed warm and cold fauna, but a cold climatic equivalent in Scotland.

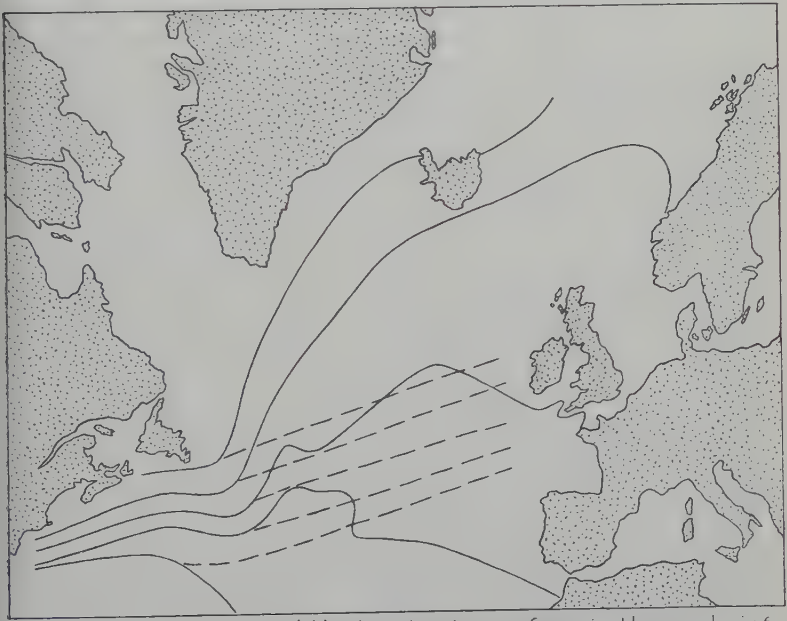
(b) The Tyrrhenian deposits have a mixed warm and cold assemblage in England, and probably throughout Scotland as well, whereas the Tyrrhenian of the Mediterranean shows a predominantly warm climate with a very slight admixture of cold.

Details for the Sicilian are not yet sufficiently worked out to allow of a similar comparison for that stage, but the mixed warm and cold fauna of the Calabrian and of the Red Crag is similar in nature to that of the Monastirian and Tyrrhenian.

Many explanations of this mixture of warm and cold indicators have been proposed. With the East Anglian Crag in mind, Harmer inclined to a theory relating to the opening and closing of barriers at the northern and southern ends of the North Sea, but obviously such an explanation will not apply to a deposit like that of Northern Lewis, nor to an area such as the Mediterranean, with the Straits of Gibraltar as its only opening to the Atlantic. The two obvious explanations are either part of a mixed fauna is derived, or part, warm or cold according to circumstance, has managed to survive from a preceding stage. To quote from an example far removed from western Europe, the derivation theory has been used by Crickmay (1929) to explain the mixed fauna of part of the San Pedro Beds of California, but although some derivation cannot be ruled out for the European deposits, the occurrence of mixtures is much too widespread here for us to accept derivation as the general explanation. Survivals from earlier faunas is also ruled out as a frequent explanation, because of the arrangement according to latitude which has been shown to occur at least in the

Tyrrhenian and Monastirian. If the correlations proposed in this paper are correct, mixed faunas are found more strongly developed in some latitudes than in others.

To the author it seems that the best explanation of the mixed faunas is to be found by assuming the temperature gradient in the eastern Atlantic was steeper in Pliocene and Pleistocene times than it is today. This hypothesis is illustrated in the accompanying sketch-map which shows, diagrammatically, the present distribution of surface isotherms of the North Atlantic (continuous lines) compared with their supposed distribution in the past (broken lines). The way in which the existing isotherms fan out towards the coast of Europe, owing to the course of the Gulf Stream Drift, shows how, at present, the cold Scandinavian fauna is kept apart from the warmer Lusitanian fauna. If it is assumed that the temperature gradient was as steep as it is now near the American coast during the Pliocene and Pleistocene periods in the eastern Atlantic, this would mean that the colder and warmer faunas of the European coasts would have lived nearer together in the past than they do now, and the mingling of the two groups



Sketch map of North Atlantic showing surface isotherms during the Pleistocene

——— *Present isotherms* ----- *Pleistocene isotherms*

Fig. 1

in a mixed belt would have been more possible than it is today. Also from the diagram it can be seen that, as one goes north of the mixed belt at any stage, the fossils will have a cold climatic equivalent, but to the south of the mixed belt the climatic equivalent will be warm. The position of the mixed belt at any horizon in the succession can be recognised in the fossil assemblage, and is found farther south at some stages than at others. From the data at our disposal it is possible to trace the movements of the mixed belt so far as it is shown by the marine formations. As we have seen, Monastirian position of this belt was approximately between the Straits of Gibraltar and the north of England. This allowed a few cold forms to enter the Mediterranean and prevented warm species from reaching as far north as the Scottish Clyde Beds. In the preceding Tyrrhenian, the mixed belt was farther north than it was during the Monastirian, allowing a considerable influx of warm immigrants to enter the Mediterranean and also making it possible to have some warm indicators as far north as Scotland. Our data for the Sicilian are not so complete as they are for the later beaches, but there is enough evidence to show that the mixed belt was very far south. From a consideration of the published lists of Moroccan fossils (Lecointre, 1950, p. 428) it extended far beyond the Straits of Gibraltar on the African coast; but did not extend as far north as Yorkshire, to judge from the intensely arctic fauna of the oldest part of the 'Bridlington Crag' beds.

Applying these ideas to the earlier deposits, the shifting of the position of the mixed belt gives a good explanation of the reduction in marine temperature during the period of the Crag in England, while at the same time accounting for the order of arrival of Gignoux's warm and cold immigrants in the Mediterranean area. If the mixed belt was as far south as Gibraltar during the Calabrian–Red Crag stage, this would explain the cold immigrants entering the Mediterranean from the Atlantic, although if the site of Suffolk was also in the mixed belt at that stage, the Mediterranean forms in the Red Crag are also accounted for. As the fauna shows that the most southerly known point of the mixed belt coincided with the Sicilian, it is not surprising that this phase in the Mediterranean can be correlated with a glaciation in the North Sea area.

If the mixed belt was somewhat north of Gibraltar in Astian times, it would have been difficult for many cold immigrants to enter the Mediterranean at that stage; but at the same date the present latitude of Suffolk could have been in the mixed belt, allowing cold conditions to make themselves felt in the Coralline Crag, although they could not affect the Astian of the Mediterranean. Thus we have an explanation of the appearance of cold conditions which began slightly earlier in Britain than in the Mediterranean.

Finally, a note must be added about the date when the temperature gradient changed from its steep Pleistocene form to its present-day condition—in other words, the geological date at which the Gulf Stream Drift assumed its existing course. As has been shown, the steeper temperature gradient is inferred from the fossil evidence, between Astian and Monastirian times, but no evidence for this steeper gradient is seen in the Holocene marine deposits. The well-known Holocene beds of Northern Ireland have a warm climatic equivalent, and there is some evidence from the Mediterranean that the Holocene marine climate there was also slightly warm, to judge from the distribution of *Purpura haemastoma* (Linn.) (Gignoux, 1913, p. 523). No hypothesis of steeper temperature gradient is needed to explain the known distribution of mollusca during the Holocene which is compatible with the climatic belts as they are today, if these belts are assumed to have been displaced bodily by a certain distance northwards. We can conclude, therefore, that the change of the state of the Gulf Stream Drift from its Pleistocene form, as depicted in the diagram, to its present-day course, took place between the Monastirian and the Holocene, i.e. approximately during the last glacial phase in Europe. A discussion of the possible causes of this remarkable change in the history of the Gulf Stream Drift lies outside the scope of the present paper.

## 5. CONCLUSIONS

Both methods of dating used in this work confirm that the British marine beds can be correlated with those of the Mediterranean. The correlation is summarised thus:

CORRELATION OF MARINE BEDS

| MEDITERRANEAN | BRITAIN |
|---|---|
| Holocene | Holocene |
| Monastirian | Portland raised beach<br>March Gravel<br>Clyde Beds, etc. |
| Tyrrhenian | Selsey Beds<br>Corton Beds<br>Wexford Gravel, etc. |
| Sicilian | Early Glacial, including Cromer Tills and part of Bridlington Crag |
| (Erosion) | (Cromer Forest Bed) |
| Calabrian | Icenian Crag<br>Red Crag<br>? Boyton Crag |
| (Erosion) | (Erosion) |
| Astian | Coralline Crag |

Only a few attempts at a general correlation between the two areas have been made in the past. Wood (1874, p. 199) wrote that he had not seen enough of the Mediterranean fossils to attempt a comparison. On the other hand, Clement Reid was able to visit some of the sections and museums of Italy, when he correlated the Monte Mario deposits, near Rome (mostly Calabrian), with the Upper Red Crag; the Lower Red Crag with the Astian; and the Coralline Crag with the Plaisancian (Reid, 1890, p. 215). Harmer's correlations were concerned more with the Netherlands than with Italy, but in discussing *Nassa ficaratiensis* (1918, p. 317), he makes a brief reference to Gignoux's Calabrian and Sicilian formations without expressing an opinion about their exact equivalents in Britain. Deperet (1920, p. 161) correlated the arctic fauna in the Bridlington Crag with the Sicilian, and also (1920, p. 215) considered Wood's 'Middle Glacial' (Corton Beds), and the Wexford Gravels, to be Tyrrhenian. Some of his other conclusions, however, do not agree with those of the present paper.

A more definite correlation has been made by King & Oakley (1949) in which they suggested that the Newbourne part of the Red Crag might be uppermost Astian; the Butley Zone could be Calabrian, and finally the Icenian was correlated with the Sicilian. A different conclusion was reached by Zeuner (1950, p. 129), who seems to favour a Sicilian age for the Red Crag. Neither of these correlations is supported by the palaeontological details in the present paper. On the other hand, the conclusions reached by Lagaaij (1952), as a result of his work on the bryozoa, agree with those of the author since he correlates (1952, pp. 203 and 206) the Gedravian (Coralline Crag) with the Astian and Plaisancian, and the Waltonian (base of the Red Crag) with the Calabrian. He does not express an opinion about the British equivalent of the Sicilian. Van der Vlerk has recently published his agreement with Lagaaij's correlations as far as they concern the North Sea basin (Van der Vlerk & Florschütz, 1953, p. 5).

If the correlations suggested here are confirmed by future work, certain consequences follow.

**Correlation of fossil mammals.** Recently many attempts have been made to correlate the Villafranchian fauna of the Val d'Arno with similar fossils in Britain. These attempts are too numerous to discuss here in detail, but it is important to remember that in defining the Calabrian formation, Gignoux (1913) stressed that *Elephas meridionalis* was contemporaneous with the Calabrian and that *Elephas antiquus* made its earliest appearance about the time of the Sicilian. If we assume that climatic differences were not too great between Britain and Italy, it is interesting to compare the dating of these elephants in the two areas. A most useful statement has been made by Boswell (1952, pp. 307–8) emphasising that *Elephas meridionalis* is associated with at least part of the Red Crag, which is to be expected if the latter is Calabrian. It is significant that *Elephas meridionalis* and *Elephas antiquus* are found together in the Cromer Forest Bed, dated by the marine beds as between the Calabrian and the Sicilian.

**Correlation of volcanic deposits.** This question does not directly affect Britain, but it may have a future importance when certain wider correlations have been made. Except for certain pre-Calabrian lavas in eastern Sicily, the volcanoes of Etna and Vesuvius are known to have started their continuous activity in Calabrian times. An example of a possible future use of the marine horizons can be seen if the volcanic history of Iceland is considered. When the Iceland 'Crag' can be dated in terms of the Mediterranean succession, it should be possible to make an instructive comparison between the rate of volcanic development in the two areas.

**Correlation of glacial deposits.** The famous glacial succession which was worked out for the eastern Alps is often correlated by archaeologists and geologists with the marine phases of the Mediterranean, but it is most important to understand that the Alpine glacial moraines are seen nowhere in contact with the marine series, and therefore such correlations are only at second hand, by way of some other kind of deposit. This is a risky, and even misleading, way in which to do geological dating, but on the other hand, frequently the glacial series in Britain, the Netherlands and North Germany is interbedded with marine deposits, and it is on the two sides of the North Sea that the marine horizons will be specially useful in helping with the glacial correlations. Space does not allow of enlargement on this topic, but it can be suggested, for instance, that if the Eem horizon is shown by future palaeontological work to be Monastirian, this would give at least one datum line for correlation.

**Correlation of Palaeolithic implements.** Round the coastal districts of southern and western Europe many sections are known which show either implements in the marine beds themselves, or in deposits interbedded with the marine phases. These critical sections are most important for dating implements in terms of the marine sequence. As one goes downwards in the succession, the interpretation of the evidence becomes increasingly controversial. On this account, therefore, the only statement which will be made here about the implements produced during the Calabrian is that the Darmsdenian pebble tools found in connection with the Red Crag in Suffolk, and the Abbevillian implements from below the Icenian near Norwich, must be associated with the Calabrian and Villafranchian, if the correlations made in the present paper are correct. No direct evidence is known to the author which would show what implements were being made in Europe during the Sicilian, but information on this point may be found in Italy at some future time. A discussion of the interesting discoveries which are being made in Portugal and Morocco lies outside the scope of this paper.

The evidence about the palaeolithic stages connected with the Tyrrhenian rise of sea-level (as distinct from non-marine deposits which are vaguely called Tyrrhenian on theoretical grounds) comes mainly from

England. In Sussex, the deep-water clay containing a Tyrrhenian fauna has been correlated by Clement Reid (1903, p. 40) with one or both of two neighbouring raised beaches at about 27 m. and 42 m. respectively above the sea; the implements from the beach shingle include Clactonian flakes and Abbevillian or Early Acheulian implements, all water-worn or rolled (Calkin, 1935, figs. 3 and 6–8, p. 338). Unrolled Middle or Late Acheulian implements occur in beds above the beach shingle (Calkin, 1935, figured on pp. 340–3), but there is much difference of opinion as to how long after the rise of sea-level these implements were made. In Norfolk, the coast section shows evidence on this point, as the Middle or Late Acheulian at West Runton is found in strata considerably younger than the Tyrrhenian Corton Beds, which themselves contain only very early Clactonian flakes (Moir & Baden-Powell, 1938). In view of this evidence, it seems that the Middle Acheulian must be dated as Post-Tyrrhenian.

During the rise of sea-level which can be dated, palaeontologically, as Monastirian, the making of Acheulian implements had almost ceased, the Levallois industry was at its height, and the Aurignacian had not yet started in western Europe. This is proved by raised beach caves at Gibraltar and in the Channel Islands, by the March Gravels (Cambridgeshire) and by many localities in Italy, including the Grimaldi caves; but the farther south one goes in the Mediterranean the more difficult it is to distinguish, palaeontologically, between the Monastirian and the Tyrrhenian stages. Some Italian geologists refer to the Monastirian beach as Tyrrhenian II, or even as Tyrrhenian.

**The Pliocene–Pleistocene Boundary.** In recent years, the tendency has been to make the first indications of a cold climate one of the characteristics of the base of the Pleistocene. If the decision of the XVIII International Geological Congress (1948) is adopted, to make the Calabrian the base of the Pleistocene, and if the Red Crag is accepted as Calabrian, then the Red Crag is the base of the Pleistocene in Britain, but it must be realised that this decision is founded on palaeontological dating and not on a recognition of the earliest appearance of a cold climate in Britain, which seems to have occurred earlier here than in the Mediterranean basin.

**Eustatic changes of level.** It is easy to recognise that some British raised beaches are at similar heights to those round the Mediterranean, but these heights mean little unless contemporaneity can be proved in some other way. The palaeontological method adopted here can be used to test whether beaches at similar or equal heights are of the same age. The fossiliferous Burtle Beds of Somerset, and the fossiliferous raised beaches at Tor Bay, Portland, Belle Hougue Cave and the March Gravels, all come within the range of height of the Monastirian beach, and they can be dated as Monastirian by their fossils. The same method can be used for the fossiliferous deposits dated by their fauna as Tyrrhenian. This applies especially to the Selsey Bed, which is correlated with beaches at heights of 27 m. and 42 m., and to the Corton Beds in East Anglia, which can be traced up to at least 25 m. and probably to a greater height (Baden-Powell & Moir, 1942, p. 212). Although many more examples await careful measurement of height, the data at present available show that the palaeontologically-dated Tyrrhenian and Monastirian beaches of southern England are at heights very similar to the undisturbed parts of the Mediterranean beaches.

A final conclusion based on such a small number of examples must be tentative, but all the heights measured so far strongly support the idea that eustatic changes of sea-level have taken place, at least for the Tyrrhenian and Monastirian stages. Unfortunately no undisturbed Sicilian fossiliferous bed has yet been found in Britain which could be used to measure the height of that marine transgression.

**The Glacial Control Hypothesis.** Acceptance of the idea of eustatic changes of sea-level is a step towards recognition of the hypothesis of Glacial Control, from which one would expect that rises in sea-level would correspond to warmer periods and falls in sea-level to colder phases. This has happened sometimes, but not consistently. Notable exceptions are seen in the low sea-level prevailing during the formation of the Cromer Forest Bed, with its mild climate, and in the cold stages represented by submergence during the Calabrian and Sicilian. Many attempts have been made to explain away these difficulties but none does so altogether. The author does not think these exceptions disprove the Glacial Control hypothesis, but rather that they show the waxing and waning of the earth's ice-sheets were not the only, or even the most important, causes of the changes of ocean-level. A broad view of the problem leads us to the conclusion that some strong unknown factor, in addition to glaciation and deglaciation, has occasionally controlled sea-level.

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## DISCUSSION

The President remarked that, in view of the decision of an International Commission to fix the Pliocene–Pleistocene boundary at a certain level of the succession in Italy (the base of the Calabrian), the paper was welcome as giving an authoritative statement as to where to draw the dividing line in this country. Correlation of marine beds in different regions of the world on purely palaeontological grounds was more difficult from the Upper Miocene onwards than in most other parts of the geological column, owing to the absence of fossils belonging to rapidly evolving and widespread groups. It was particularly interesting to know that the author had found evolutionary changes in certain species of *Turritella* to be helpful in correlating English beds with those in Italy. In certain parts of the Indo-Pacific province (Indonesia, Burma, Pakistan) *Turritella* occurred in great abundance and variety throughout the Neogene succession. Palaeontologists had tried in vain to distinguish evolutionary trends which would assist in correlation, and had decided that it was only possible to regard the great majority of specimens as belonging to a single highly variable species.

The President further remarked that the expression 'eustatic changes', used in the summary of the paper, had attracted his attention. This and the similar term 'eustatic movements', although now part of geological terminology, seemed ill-chosen and self-contradictory, since from its derivation (Greek: *εὐσταθῆς*, steadfast, stable) the adjective 'eustatic' indicated an absence of movement. The explanation of the original choice of the word was presumably the involved one that the movements referred to were relative to land which was considered to be stable. In other words, the land and not the movements might more properly be termed 'eustatic'.[1]

DR. J. D. SOLOMON welcomed the paper as a valuable attempt to establish a sound palaeontological basis for Pleistocene correlation. He pointed out, however, that in so far as a succession depended on raised beach material it was liable to be incomplete; all traces of a comparatively small rise of sea-level due to a minor interglacial might be wiped out by a subsequent greater one.

In this connection he would like to know what stage the author considered to correspond to the rise in sea-level that must have accompanied the formation of the very important Boyn Hill terrace. The usual assumption that the Goodwood terrace was of this age would have to be abandoned if there was firm palaeontological correlation between Goodwood and Corton. For similar reasons, he felt that a confident correlation of the Bridlington Crag with the Sicilian stage required stronger evidence than the author had brought forward.

PROFESSOR S. W. WOOLDRIDGE said that it was a matter of continual surprise to him that orthodox geological opinion had for so long ignored the fact of eustatic shifts of sea-level. That such shifts must have accompanied the waxing and waning of the ice-sheets was of course beyond all question, but it was important to note that as Professor Zeuner had shown, these oscillations had been superimposed on an over-all drop of sea-level which seemed to have been in progress since Cretaceous times. The highest late-tertiary sea-level in south-east England was registered by the high-level deposits of sand and shingle at about 600 ft. O.D. which it had been usual to assign to the Pliocene, though in view of the now received opinion which assigned the Red Crag to the Pleistocene it was clear that these deposits were of early Pleistocene age. There could in fact be little doubt that the transgression of the sea in question represented the Calabrian stage of Southern Europe. The speaker welcomed very cordially the evidence adduced by the author which provided some independent palaeontological evidence of the sequence of the sea-level stages.

DR. K. A. JOYSEY congratulated the author on the completion of his work, which was of fundamental interest in several fields of study. He particularly wished to compliment the author on his lucid description of the changes which had occurred in the distribution of the marine mollusca. The author had described a mixed belt in which 'warm indicators' and 'cold indicators' overlapped in their distribution, and he had shown that this mixed belt had occupied different latitudes at different periods of time.

[1] Subsequent to the meeting it was ascertained that the term 'eustatische Bewegungen' (eustatic movements) was coined by E. Suess (1888, *Das Antlitz der Erde*, Bd. 2, p. 680) with the definition (English translation) 'changes which affect the level of the strand . . . which take place at an approximately equal height, whether in a positive or negative direction, over the whole globe'. The comment that 'eustatic' was a most inappropriate adjective to be given this connotation is not affected by the eminence of the worker who introduced it into the terminology.

During recent years Southward & Crisp (1954) had studied the present distribution of several intertidal species of gastropods, barnacles and echinoderms around the Irish and British coasts. The species which had been studied included some 'southern forms' which reached the northern limit of their distribution around the British Isles. It had been found that such species were more abundant, in their individual numbers, on the west and south coasts, than was the case on the east and north coasts, while some species were confined to the west and south coasts.

It would be of interest to try to assess the stability of this pattern of distribution. The speaker wished to inquire whether any of the fossil species showed a distribution analogous to that of the present-day fauna and whether there was any evidence that, at any given time, the 'mixed belt' on the western side of the British Isles was situated at a higher latitude than on the eastern side.

THE AUTHOR, in reply to the President's comments on the meaning of the word 'eustatic', admitted that a term like 'eustatic changes' was unfortunate, but the expression was perhaps permissible if taken to mean change from one stable position of sea-level to another, on the understanding that the height of the sea remained for an appreciable length of time at each 'stillstand'. The part of the paper which dealt with evolution in certain species of *Turritella* was based on evidence of identical forms which occurred in Britain and the Mediterranean area.

In replying to Dr. Solomon's question about the marine equivalent of the Boyn Hill terrace of the Thames, the author thought it possible that the estuarine bed connected with the Clacton Channel in Essex might afford the evidence needed, but the only fauna known from this bed so far is very indefinite in character. No marine phase is known otherwise which can be correlated with this stage either in the case of the Thames or of the Somme. The correlation of the Corton Beds with the Goodwood raised beach of Sussex is sound palaeontologically, and both these marine deposits appear to be earlier than the Middle Acheulian archaeological stage. In answer to Dr. Solomon's question about the Bridlington Crag, it was pointed out that in the last years of his life, Searles Wood considered the Bridlington Crag fauna to be contemporaneous with the North Sea Drift of East Anglia, and therefore earlier than the Corton Beds.

Professor Wooldridge pointed out that the height of the Lenham Beds in Kent (about 600 ft. O.D.) was approximately the supposed height of the Calabrian sea-level; he in fact asked whether the Lenham Beds might be of Calabrian age. The author replied that he understood the Lenham fauna was difficult to identify in detail because the shells were mostly in the form of casts but he understood that many of the genera present were of an Astian rather than a Calabrian type, if not Pre-Astian. As regards their height, the level of the Calabrian submergence was difficult to determine in the Mediterranean area, owing to later earth-movements, and in places in Sicily the Calabrian beds are found as high as 1800 ft. above the present sea.

In reply to Dr. Joysey's question about the differences of present-day distribution between the western and eastern coasts of the British Isles, the author replied that these differences were relatively small in this case, whereas the warm and cold indicators involved in the 'mixed belts' during the Pleistocene represented a much more extreme difference. In some cases species which now live as far apart as Scandinavia and the Mediterranean are found as fossils in the same deposits.[1]

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[1] After the meeting, the author remembered that there is actual evidence of colder conditions in Eastern Scotland, as compared with Western Scotland, at the time of the deposition of the Clyde Beds.

# Note on the Fauna of an Early Holocene Tufa at Wateringbury, Kent

by M. P. KERNEY

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SEVENTEEN years ago E. E. S. Brown published an account of a newly-discovered Holocene tufaceous deposit at Wateringbury, Kent, and to this was appended a report on the contained non-marine mollusca by the late A. S. Kennard (Brown & Kennard, 1939). From the list of shells it was clear that the tufa was a remarkable one and deserved further investigation. Therefore, in 1953 large new collections were made by the writer, with some interesting results. Since the general relations and the lithology of the deposit have been admirably described by Mr. Brown, this note is concerned solely with the fauna. Forty-one species of mollusca are now known, together with three mammals.

## FAUNAL LIST, WATERINGBURY, KENT

MAMMALIA

| | |
|---|---|
| **Clethrionomys cf. glareolus* (Schreber) | Mature right $M_1$. |
| **Microtus agrestis* (Linné) ... ... | Right $M_1$. |
| **Neomys? sp. indet.* ... ... ... | Fragmentary right mandibular ramus, lacking teeth. This may be referable to *Neomys fodiens* (Schreber), but the specimen is too imperfect to allow exact determination. |

MOLLUSCA

| | |
|---|---|
| *Pomatias elegans* (Müller) ... ... ... ... | 9 |
| **Acme fusca* (Montagu) ... ... ... ... | 5 |
| *Carychium minimum* Müller ... ... ... ... | very abundant |
| *C. tridentatum* (Risso) ... ... ... ... | very abundant |
| *Limnaea truncatula* (Müller) ... ... ... ... | 54 |
| *Succinea pfeifferi* Rossmässler ... ... ... | 12 |
| *Cochlicopa lubrica* (Müller) ... ... ... ... | 226 |
| **C. lubricella* (Porro) ... ... ... ... ... | 14 |
| *Columella edentula* (Draparnaud) ... ... ... | 220 |
| *Vertigo pusilla* Müller ... ... ... ... | 128 |
| *V. substriata* (Jeffreys) ... ... ... ... | 184 |
| **V. moulinsiana* (Dupuy) ... ... ... ... | 14 |
| **V. alpestris* Alder ... ... ... ... ... | 8 |

| | |
|---|---|
| *Lauria cylindracea* (da Costa) | 69 |
| *L. anglica* (Wood) | 104 |
| *Acanthinula aculeata* (Müller) | 188 |
| *A. lamellata* (Jeffreys) | 192 |
| *Vallonia costata* (Müller) | 432 |
| **Ena obscura* (Müller) | 3 |
| **Marpessa laminata* (Montagu) | 25 |
| *Clausilia bidentata* (Ström) | 84 |
| **Balea perversa* (Linné) | 16 |
| **Cecilioides acicula* (Müller) | 2 |
| **Helicigona lapicida* (Linné) | 2 |
| *Arianta arbustorum* (Linné) | 4 |
| **Helix hortensis* Müller | 8 |
| *H. nemoralis* Linné | 7 |
| **Hygromia striolata* (C. Pfeiffer) | 31 |
| *H. hispida* (Linné) | 72 |
| *Punctum pygmaeum* (Draparnaud) | 350 |
| *Discus rotundatus* (Müller) | 554 |
| *Arion sp.* | 622 |
| *Euconulus fulvus* (Müller) | 187 |
| *Vitrea crystallina* (Müller) | 452 |
| *Oxychilus cellarius* (Müller) | 117 |
| *Retinella radiatula* (Alder) | 255 |
| *R. pura* (Alder) | 221 |
| *R. nitidula* (Draparnaud) | 234 |
| *Vitrina pellucida* (Müller) | 3 |
| '*Limax*' *sp.* | 39 |
| **Pisidium personatum* Malm | 17 valves |
| Ova of helicoids | 230 |

Numerals in the right hand column indicate numbers of specimens found.

* Indicates a new record.

As Kennard stated, there is no doubt that many of these snails are now locally extinct. Moreover, four species, *Vertigo pusilla*, *V. moulinsiana*, *V. alpestris* and *Lauria anglica* are quite unknown alive in the county. *Vertigo alpestris* is perhaps the most remarkable of these, as it has not been recorded living in England south of Yorkshire, and hitherto has not been found in Kent either recent or fossil. *V. moulinsiana* is very rare as a fossil, though known sporadically from the Pleistocene of Clacton (Great Interglacial) onwards.

At the present day *Acme fusca*, *Vertigo pusilla*, *V. substriata*, *Lauria anglica* and *Acanthinula lamellata* have a distinct northerly or westerly distribution in the British Isles, but it is clear that these species were more widespread once, and are particularly common in the Early Holocene of Essex. A stronghold of such forms, today, is provided by the more oceanic climate of Ireland.

Kennard lists but two examples of *A. lamellata*, but recent collecting has proved it is plentiful. This still remains the only fossil occurrence in Kent.

*Carychium* was very abundant in the tufa. In a count of one thousand specimens of *Carychium spp.* 115 were *C. minimum* and 885 *C. tridentatum*.

Kennard's record of *Helicella itala* is somewhat puzzling, as the species did not occur in recent gatherings, and, being a xerophile, it would be out of place in the assemblage. It is possible that his single example was an immature or imperfect shell of *Hygromia striolata*, a form which does not figure in his list, though common, and which *H. itala* closely resembles when young.

It is noteworthy that only *Pisidium personatum* can be called truly fresh-water, and even this species will survive the drying up of its habitats for considerable periods. No doubt many of the mollusca lived and died almost where they are found today, on the swampy delta in which the tufa formed, but trees were close at hand to provide such typical old-woodland species as *Acme fusca*, *Acanthinula lamellata*, *Lauria anglica* and *Helicigona lapicida*. Pieces of charcoal and fragmentary impressions of leaves are common in the deposit, as are traces of marsh vegetation.

In all samples taken, small calcareous tubes belonging to a caddis fly larva were abundant, and it is interesting to note that La Touche refers to the frequent occurrence of similar tubes in the tufas of Burma (La Touche, 1913). Unfortunately caddis-cases cannot be determined generically.

## CONCLUSIONS

The conclusions reached by Kennard as to climatic conditions are fully supported by our better knowledge of the fauna. The mollusca are almost all damp-loving forms and give evidence of a period of heavy rainfall when the optimum conditions for their well-being were present. Mean annual temperatures may also have been higher. Such conditions are known to have occurred in the Atlantic period, which roughly coincided with the Late Mesolithic and Neolithic Ages in this country (*c.* 5000–2500 B.C.), and to this time may also be referred the tufas of Broughton, Lincolnshire (Kennard & Musham, 1937), the many swamp deposits of Essex and that of Wilstone, near Tring, and the famous Blashenwell tufa in Dorset (Bury, 1950). Marsh deposits of Atlantic date are now known from many parts of Britain. Their molluscan faunas are invariably richer than those living in analogous situations at the present time, the swamp peat at Tilekiln Green, Essex, having yielded a greater number of species of land-snails than any other Quaternary deposit in the British Isles (Kennard *in* Warren, 1945).

Today, a search in the immediate area of the Wateringbury tufa yielded but ten species, including two which are post-Roman invaders and not found in the deposit. As elsewhere, clearly a great impoverishment of the local fauna has taken place.

## ACKNOWLEDGMENTS

My grateful thanks are due to the following for their kind help in connection with this note: J. N. Carreck, for naming the mammalian remains; A. W. Stelfox for identifying the *Pisidia*, and A. G. Davis, above all, for his constant assistance so freely given.

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# The Namurian Usk Anticline

by T. NEVILLE GEORGE

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**ABSTRACT:** The Armorican Usk anticline displays evidence of 'Sudetic' and possibly 'Malvernian' antecedents, details of which may be elucidated by the use of interpolated and deduced isopachytes. A reconstructed map of the sub-Namurian floor indicates that the present form of the fold was closely delineated during mid-Carboniferous times in the ground between South Wales and the Forest of Dean.

On Titterstone Clee Hill the Cornbrook Sandstone belongs to the Millstone Grit, and oversteps Avonian rocks on to Old Red Sandstone. The general relations of the strata suggest that the outlier once occupied part of the eastern flank of a northern extension, or northern homologue, of the Namurian Usk fold.

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## 1. STAGES OF GROWTH

### (a) Evidence of repeated movement

THE USK ANTICLINE, separating the South Wales coalfield from the Forest of Dean, is a structure mainly of Armorican age. It culminates in a faulted pericline, the core defined by an outcrop of Silurian rocks, that has an anomalous north–south alinement like that of several neighbouring and related structures—the Dean Forest syncline, the Bristol coalfield and the Malvern range. Southwards and south-westwards the axial trend takes up a more 'normal' direction, continuing uninterruptedly into the Roath pericline at Cardiff and thence (with a marked veering) into the typically armoricanoid east–west Cowbridge anticline of the Vale of Glamorgan, across which gently dipping Triassic rocks transgress in a distance of a few miles from Pennant Sandstone on to Wenlock Shales and prove the age of the fold.

For a score of years, however, there has been increasing recognition, based on the work of Dixon (in Strahan, 1909, p. 20) and Dixey & Sibly (1918, p. 123), that the Usk anticline, while in the main an Armorican orogenic product, was significantly advanced in growth long before the end of Carboniferous times—at least as an upwarp forming the eastern margin of the South Wales basin. The evidence of its growth is provided by progressive Namurian overstep eastwards across Visean and Tournaisian zones, which suffer a maximum reduction (in the present outcrops) on Blorenge, near Abergavenny, where the whole of the Avonian Main Limestone is transgressed and only the Lower Limestone Shales remain (Pringle & George, 1935, p. 70 and fig. 20). Recently, detailed analysis of the relations of the Millstone Grit and the Carboniferous Limestone has allowed the precise nature of the overstep to be determined more completely and the Namurian form of the upwarp to be discerned (George, 1954, p. 311; 1956, p. 315).

A recurrence of movement in Upper Carboniferous times is shown by the eastward thinning of the Coal Measures in Monmouthshire, where Moore (1948, p. 290, fig. 9) and Blundell (1952, p. 312, fig. 2) have demonstrated that comparable strong unconformities below and within the Pennant Series may also be attributed to contemporaneous uplift of the eastern margin of the coalfield, which was thus repeatedly emergent to the extent of several thousand feet—an estimated 2700 ft. in the six miles from the Caerphilly basin to the East Crop—before the final imposition of the existing structural form in late-Carboniferous or post-Carboniferous times.

### (b) **Intra-Carboniferous structural form**

At the same time, a notable difference between the Namurian ('Sudetic') and the Westphalian ('Malvernian') phases of movement is indicated by the Carboniferous succession in the Forest of Dean.

On the one hand, while on the East Crop Main Limestone is completely overstepped near Abergavenny, across the Usk axis it returns in strength—though not completely—along the whole western flank of the Dean Forest basin. The sub-Namurian structure in the Avonian strata was therefore a true arch, and may fairly be regarded as broadly ancestral to the existing anticlinal fold.

On the other hand, the Upper Carboniferous rocks of the Dean Forest basin are very incompletely represented as compared with their counterparts of the East Crop. Nowadays Millstone Grit is completely absent (though it occurs farther south, beyond Chepstow, and may be supposed to have had a pre-Westphalian extension into the Forest); and Lower Coal

Measures (of Ammanian age) are also unknown. The local basal Upper Carboniferous beds, the Trenchard Group, are of Morganian (Middle Pennant) age.

In its bearing on the possible occurrence of intra-Westphalian Usk folding, as distinct from simple uplift or tilting, the present-day residual evidence is thus equivocal. A control upon sedimentation exerted between the East Crop and the Forest of Dean by a growing Westphalian anticline certainly could account for the stratigraphical differences between the two areas. But so could persistent eastward overlap of Namurian and Ammanian strata (Trotter, 1942, p. 6), or overstep by the Morganian Pennant Series across older beds of whatever age (Trueman, 1947, p. lxxi; Moore *in* Trueman, 1954, p. 127): in either case without the occurrence of an intervening Usk arch. It is significant that the greatest extent of Westphalian overstep occurs on the eastern flank of the Dean Forest basin, where horizons not far below the base of the Upper Pennant Group come to rest on Lower Old Red Sandstone—perhaps on the flanks of a rising Malvern ridge. Elsewhere in the Welsh border country the Morganian stage also shows a tendency not to run with the Namurian and often not to be obviously influenced by recrudescent folding along earlier Carboniferous lines.

### (c) The reconstructed Namurian fold

The detailed changes in all members of the Carboniferous succession are now well known in South Wales, and form a starting-point for the present study. But elsewhere the Coal Measures are widely stripped, and the Millstone Grit almost completely stripped, from the region of the Usk anticline, and it is not possible to surmise, even in vague outline, the stages of Usk-anticlinal growth in Upper Carboniferous times—for the occurrence of which there is indeed neither proof nor bias of evidence. The residual outcrops of Carboniferous Limestone, on the other hand, including the correlated outcrops of Titterstone Clee Hill where, by erosional chance, a relic of the Millstone Grit is also preserved, are sufficiently extensive on the east and south-east flanks of the fold to allow a reconstruction of its approximate form in early Namurian times. The reconstruction is summarised in Fig. 1.

Two assumptions are made in the reconstruction. One is that no appreciable discordance between the *Dibunophyllum* and the *Seminula* Zones occurred in former extensions of the beds: at all known present-day junctions in the South-Western Province conformity appears to be complete. The other—scarcely an assumption—is that existing sub-Westphalian occurrences of Avonian zones were no less extensive in Namurian times, even where no Millstone Grit now remains to prove the point.

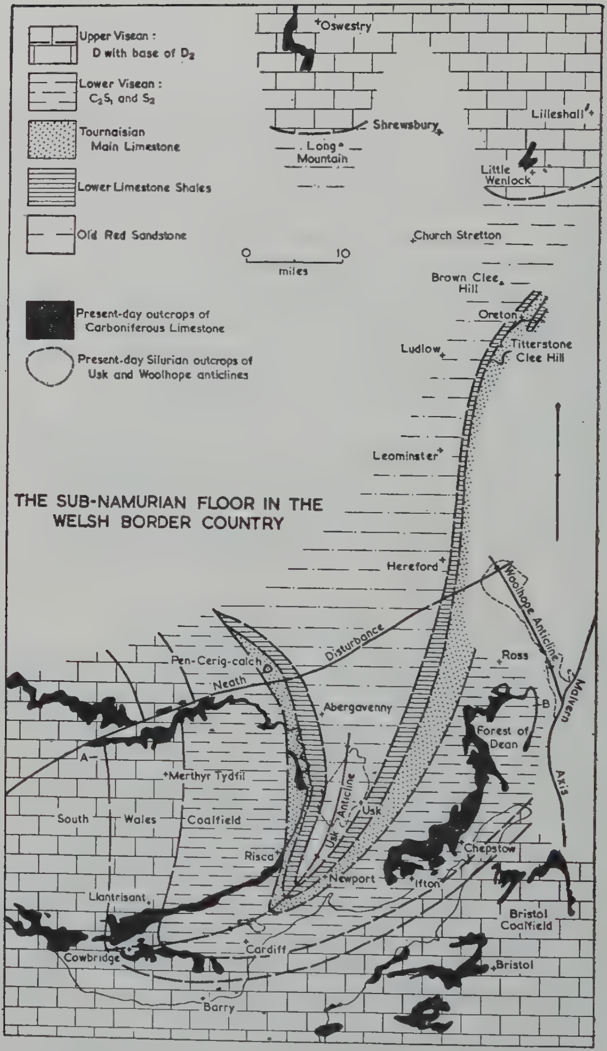

Fig. 1. Reconstruction of the sub-Namurian floor in the Welsh border country, to illustrate contemporaneous folding of the Usk anticline

## 2. SOUTH WALES

### (a) The northern and eastern tracts

The zero isopachytes of the Avonian zones in South Wales, closely pinned for the Visean Main Limestone on the North and South Crops, and for the Tournaisian on the East Crop, provide very clear and precise stratum-contour evidence of the form of the western flank of the Namurian anticline. Extrapolation of the transgressive Namurian base a short distance beyond the present outcrops between Abergavenny and Risca strongly suggests that sub-Namurian extinction of the Lower Limestone Shales also occurred well to the west of the existing anticlinal axis, and that along the axial crest Millstone Grit rested directly on Old Red Sandstone—probably Lower Old Red Sandstone. The trend of the isopachytes is broadly north–south, though those running close to the present East Crop have a slight curvature, like the Crop itself—and like the fold-axis partly defined by the Crop (see George, 1956, p. 315 and fig. 6).

It is evident that the various Avonian zones formerly extended beyond the North Crop into Central Wales. Their sub-Namurian trend is uncertain, however. For many miles west of the Neath disturbance, the Millstone Grit runs with the Upper Limestone Shales without notable discordance, and the present outcrop corresponds more or less with the depositional strike. Namurian overstep into Central Wales, if it formerly occurred, was controlled in this ground by the southern borders of the massif of St George's Land, the Usk fold being too distant to have had any effect.

The 'caledonoid' Neath disturbance was itself a zone of movement in early Carboniferous and mid-Carboniferous times (George, 1954, p. 311, fig. 9), but only the small outlier of Pen-Cerig-calch now remains in the ground where the disturbance runs towards the Usk axis. The surviving evidence is inconclusive, but the mutual effects of the two lines of movement place the outlier (carrying a remnant of the Tournaisian Oolite Group beneath Millstone Grit) on a sub-Namurian erosional strike trending towards the west flank of Blorenge. If this trend is an indication of conditions generally in the syntaxial region, it suggests a gentle swing of the isopachytes towards the north-west, presumably to take up in no great distance the basic armoricanoid grain of South Wales. It may then be concluded that along the Usk line the sub-Namurian outcrop of Old Red Sandstone broadens northwards, up the pitch of the fold.

The residual evidence is inadequate to resolve the separate degrees of Seminulan and Namurian overstep north of Pen-Cerig-calch, but the tapering-out of Tournaisian Main Limestone beneath Visean beds may be inferred with confidence. It is probable that the trend of the base of the Main Limestone is also a fair guide to the trend of the sub-parallel base of the Lower Limestone Shales, which may have been likewise extinguished north-westwards by Seminulan and not sub-Namurian overstep. A hint is given (but far to the west) by the northward thinning of the Shales beneath the *Seminula* Zone along much of the North Crop: at Careg-yr-ogof in Carmarthenshire—the northernmost exposure on the Crop—the Shales are reduced to a mere 15 ft.

### (b) **The southern tracts**

In the Vale of Glamorgan the rocks of the Avonian outcrops lie along the Gower–Bristol depositional strike, and mostly belong to thick 'standard' facies-zones in all the beds remaining. The highest visible strata are low Visean in age (Sibly, 1920, p. 89)—Upper Caninian and possibly lowest Seminulan—and although the *Dibunophyllum* Zone is not seen (being hidden under a Mesozoic cover) it may be supposed to have been present, formerly, beneath Millstone Grit along at least part of the crop which runs east from Cowbridge. On the South Crop the sub-Namurian D–$S_2$ junction is precisely located near Llantrisant (Dixey & Sibly, 1918, p. 148), where it has a southerly trend. South of this point, therefore, it must make a sharp eastward bend to run towards Cardiff without encroaching unduly on the Cowbridge outcrop. The angle of flexure appropriately lies on, or very near, the axis of the Cowbridge anticline.

It is conceivable that the inferred position of the line near Cardiff lies too far north, for, in the zones exposed, the Barry limestones are more typically 'standard' than their equivalents just south-west of Cardiff, and in that respect may be a pointer to an equivalent change at the Visean-Namurian junction. But the generic structure of the sub-Namurian floor would not be altered significantly if the line were moved a short distance to the south: and the distance would need to be short—no more than a few miles—to maintain without marked irregularity the sweep of the line into the Chepstow country.

Where the East Crop runs into the South Crop the disparity in dip between the Millstone Grit and the Carboniferous Limestone reaches a maximum near Risca, where it is of the order of five or six degrees. The zero isopachytes of Visean and Tournaisian Main Limestone are thus crowded and imply relatively acute Usk folding. They also run somewhat west of south. Nevertheless they cannot maintain this course for many miles without approaching the D–$S_2$ junction near Cardiff. In Fig. 1, therefore, they are made to change direction on the crest of the Usk fold about five miles north-east of Cardiff. The site of the change is selected only to maintain the smooth lines of the known structures for it is but vaguely indicated by existing Visean outcrops in the ground north of Barry and in Flat Holm and Steep Holm (Smith & Wilson, 1937). There is no residual evidence in its immediate neighbourhood to prove its position, and perhaps the lines should be moved towards the Roath Silurian inlier, or perhaps there was a secondary culmination at the inlier. But the permissible range of movement is not wide, and the general form of the fold nose in the Tournaisian rocks, as shown in the figure, cannot be greatly erroneous. Nor can the nose be moved far to one side or other of the existing axial line except a gratuitous postulation of marked irregularities of isopachyte trend, and the two are nearly, if not quite, coincident.

The position of the anticlinal nose at the Avonian base is more speculative, but not unduly so, since it must lie within the Visean base. The form of the Avonian base is indicated as a simple curve: whether there was a contemporaneous culmination at the site of the present Silurian pericline is unknown, of course.

## 3. THE BASINS OF SOMERSET AND GLOUCESTERSHIRE

### (a) **The Bristol and Somerset coalfields**

At the present day the Forest of Dean has a synclinorial structure and is separated from the basins of the Bristol and Somerset coalfields by a partly buried extension of the Malvern ridge which may have had a long geological history. The complex sub-malvernoid folds of the region (Moore & Trueman, 1939) nevertheless appear not to have had any significant effects on the Avonian succession, and therefore would seem to be post-Namurian in age.

South-east of the Severn estuary the relations of Millstone Grit and Carboniferous Limestone are uncertain, partly because an arenaceous facies of Millstone-Grit lithology (notably the Brandon Hill Grit of the Bristol area and the thick Cromhall Sandstones of the northern rim of the Bristol coalfield) becomes strongly represented in the upper Visean beds and partly because faunal evidence of Namurian zones is sparse. In Bristol itself the Pendleian stage seems to be represented (Moore, 1941), and goniatites of the *Euomphoceras* Zone are known from Broadfield Down (Kellaway & Welch, 1955, p. 18) and possibly of the *Gastrioceras* Zone from the Mendips (Welch, 1931). Elsewhere, what may be true Millstone Grit shows wide fluctuations in thickness, and the relations of Upper and Lower Carboniferous strata seem to be determined by unconformity of variable intensity at the local base of the Coal Measures.

In contrast, there are few if any contacts in the Bristol–Somerset ground where an appreciable discordance can be recognised between Millstone Grit and Carboniferous Limestone; and although in places the sub-Westphalian unconformity descends to low Visean horizons (Moore & Trueman, 1939, p. 61), its effects are not to be regarded as partly inherited from an antecedent sub-Namurian unconformity of comparable magnitude. Not only in the Bristol area and Broadfield Down, but also in the Mendips and in the rim of the Bristol coalfield, beds high in the *Dibunophyllum* Zone are well represented and point to a former regional extension beneath the Millstone Grit (Kellaway & Welch, 1948, p. 21).

From the evidence of the outcrops now visible it appears, therefore, that the whole of the ground south-east of the Severn estuary was a tract of Carboniferous sedimentation subsiding virtually continuously from Avonian into Namurian times. There is no evidence of control by an Usk anticline to be seen anywhere in the succession, but presumably the floor of the tract was gently falling away from the fold crest, as delineated in Fig. 1 by the sub-Namurian D-Zone isopachytes near Chepstow. Nor is there any anticipatory hint of a 'Lower Severn' anticlinal axis that, possibly as an off-shoot of the Malvern line, may have had an amplitude in mid-Westphalian times of the order of 5000 ft. (as indicated by a transgression of the Pennant Series on to Old Red Sandstone), along the western border of the Bristol coalfield (Kellaway & Welch, 1948, p. 29 and fig. 8).

### (b) The Chepstow and Dean Forest synclines

To the north-west of the Severn estuary the Avonian rocks present a generally uniform succession from the Chepstow district into the Forest of Dean. The only considerable change is the intensification of the Visean sandy facies as the Drybrook Limestone passes laterally into the Drybrook Sandstone. Since the Limestone is of Seminulan age, it is probable that the Sandstone is of this age also, though the uppermost beds (part or all of the Upper Drybrook Sandstone) may belong to the lowest *Dibunophyllum* Zone in the ground about Chepstow (Trotter, 1942, p. 12; Kellaway & Welch, 1948, p. 21). Obviously the present stratigraphical break above the Visean rocks in the Dean Forest basin is attributable to sub-Westphalian unconformity, but in the complete absence of Millstone Grit from the rim of the basin (through either overstep or overlap) it is impossible to determine whether there was also pre-Namurian uplift and erosion.

Dixon (1921), by analogy with similar occurrences in South Wales, has described a now-famous instance, at Ifton south-west of Chepstow, of pot-holing and channelling of limestone surfaces (in rocks of $S_2$ age) before deposition of gritty sandstones and shales referred to the Millstone Grit. The rocks of the exposure, isolated and remote, are not readily correlated with those of other areas. Perhaps the most that can be said of them is that they lie in a position relatively off-shore in the broad palaeogeographical environment of Carboniferous sedimentation; and on such slender evidence it may be inferred tentatively that, in the ground to the north and north-east, higher Avonian beds than the Ifton Seminulan limestones were not preserved beneath the Millstone Grit. In Fig. 1, therefore, the sub-

Namurian D–$S_2$ junction is made to run between the Chepstow syncline and the Bristol coalfield.

The whole argument, precarious as it is, may be vitiated altogether if the Ifton sandstones should prove to belong not to the Millstone Grit but to the Coal Measures—a possibility recognised but on balance rejected by Dixon, who regarded them as lithologically most like the Namurian Basal Grit. Nevertheless, even if they are of Westphalian age the map would be modified only by becoming vaguer: the sub-Namurian D–$S_2$ junction could then lie anywhere in a broad zone embracing the Forest of Dean and the outcrops to the south; but it must lie north-west of the Bristol coalfield, and, as drawn in Fig. 1, it lies in a possible but rather extreme south-easterly position. In the Chepstow ground the Drybrook beds are about as thick as the whole *Seminula* Zone on the west flank of the Bristol coalfield, and little of the zone could have been removed before deposition of the Millstone Grit (or the Coal Measures). If the Ifton sandstones belong to the *Dibunophyllum* Zone as an outlier of the Cromhall (Drybrook) Sandstones (Kellaway & Welch, 1955, p. 18), the sub-Namurian D–$S_2$ junction should be located well to the north-west of the Severn estuary.

There is less room for play in the stratum-contours at lower horizons. Given the evidence of the East Crop in South Wales, and of the persistence of the *Seminula* Zone along the whole western edge of the Dean Forest and Chepstow synclines, the sub-Namurian zero isopachytes of the lower Visean and Tournaisian zones on the east flank of the Usk fold must necessarily lie between the fold crest and the existing outcrops. Although determined circumstantially (there being a complete lack of direct evidence), the position and trend of the lines shown in Fig. 1 are of the right order, at least as far north as the latitude of Abergavenny. Doubtless they have an artificial smoothness, the actual lines having been affected by minor flexures like those of South Wales. But the reconstruction of the Namurian fold is sufficiently complete to bring out the close relationship between the existing Armorican axis and the early Namurian axis, and to leave little doubt that the site of the one was partly conditioned by the site of the other.

The deduced structure across the Usk anticline in Monmouthshire during Namurian and Westphalian times is illustrated in Fig. 2.

North of the Forest of Dean, towards Hereford, the lines on the map are highly speculative and have almost no validity. The Woolhope anticline in many of its features compares with the Usk anticline, and is a product of the same orogenic forces. It may well have originated in Carboniferous times and have similarly affected Namurian (if not Avonian) sedimentation. The Dean Forest tectonic basin conceivably reflects a depositional basin with closure to the north, lower Visean beds having been overstepped by Millstone Grit a short distance beyond the present outcrops.

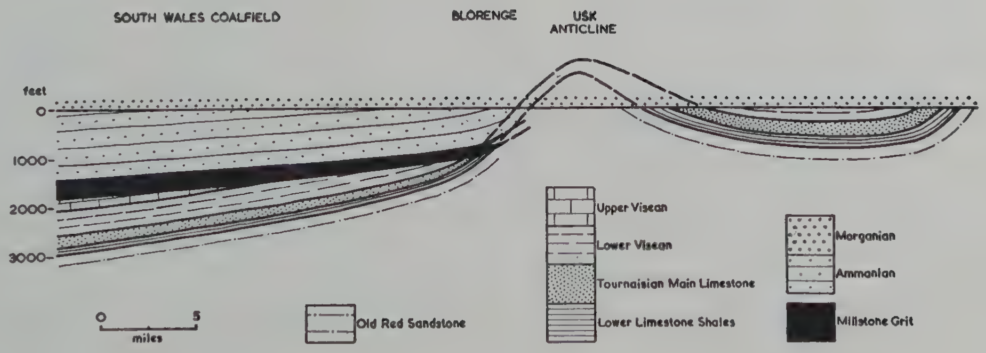

Fig. 2. Reconstructed section, along the line A–B of Fig. 1, across the Usk anticline in Morganian times. The Westphalian relationships after Trueman & Moore

Such speculations are more or less idle, however: they serve but to cast doubt on any reconstruction in the Hereford–Leominster country, where the lines on the map are intended to have only the function of linking up the southern development with that on Titterstone Clee Hill.

## 4. THE AGE OF THE CORNBROOK SANDSTONE

### (a) The Carboniferous Limestone of Titterstone Clee Hill

The rocks about Oreton and Studley, remote outliers of the South-Western Province on Titterstone Clee Hill, have been described by Vaughan (1905, p. 252) and Dixon (1917, p. 1064; Whitehead & Others, 1929, p. 42), who showed that the calcareous facies is wholly Lower Avonian, and who thought that the overlying Cornbrook Sandstone is also Avonian (probably early Visean) in age. They inferred that the sandy facies descends diachronously to such low horizons in simple continuation of the trend displayed by the Avonian sediments of the Bristol coalfield and the Forest of Dean. The evidence outlined below, however, leads to the conclusion that the Cornbrook Sandstone rests upon the beds beneath with marked unconformity, and that it truly belongs to the Millstone Grit in which it was originally placed on lithological grounds.

The Lower Limestones Shales are not well exposed, but wherever they are seen they are typical members of the *Cleistopora* Zone, as Vaughan recognised, comparing in thickness with the development on the North Crop in Monmouthshire. They consist of alternating thin-bedded shales and impure dark limestones, richly fossiliferous with abundant specimens of *Spirifer* (*Cyrtospirifer*) cf. *tornacensis* de Koninck, *Syringothyris* sp., athyrids, *Hustedia* sp., camarotoechiids, and *Dictyoclostus vaughani* (Muir-Wood).

Nowadays the succeeding Main Limestone is poorly exposed in the old overgrown quarries at Gorstley and Studley, where only occasional ribs of dolomitic limestone with interbedded buff marls can be seen. Along the northern outcrop at Oreton, however, almost the full succession is exposed in the quarries still being worked. It consists mainly of massive beds of organic-fragmental (strongly crinoidal) limestone and oolite. Some of the oolitic beds are almost 'pure' in consisting of well-formed ooliths of more or less uniform size set in a clear recrystallised calcitic matrix. Oolitic structure is also common in many of the crinoidal layers, if only as ooliths composed of thin skins about the coarsely-granular crinoid cores. With the crinoids, polyzoans form a considerable proportion of the rock, and comminuted shell fragments are abundant. Well-preserved macro-fossils are common in some layers and include, in addition to the forms listed by Vaughan (*idem*), *Spiriferellina* sp., *Schizophoria* sp., and molluscs. Some of the beds are patchily dolomitised; and a decalcified buff shale or marl is prominent in the upper part of the succession.

The whole group closely resembles, though it is rather more richly crinoidal than, the Oolite Group of the North Crop in Breconshire, and the lithological evidence strongly favours the conclusion that there was continuity of sedimentation in much the same facies between the two areas.

### (b) The unconformity beneath the Cornbrook Sandstone

The Oreton limestones are not much more than 40 to 50 ft. thick at a maximum, whereas the Oolite Group is 160 ft. thick—and even then represents only the lower Tournaisian Main Limestone. If the Cornbrook Sandstone follows the limestones conformably, it is scarcely referable to Visean zones but must be of Tournaisian age (at least in its lower beds). Elsewhere a coarse thick false-bedded deltaic gritty sandstone is completely unknown at Tournaisian horizons in the South-Western Province, and the lithological relations cast doubt on the assumption of conformity. The field evidence shows that the doubt is justified.

Dixon (1917, p. 1067) considered that 'the junction with the Carboniferous Limestone Series . . . is . . . undoubtedly a conformity' because, as he thought, the Cornbrook Sandstone everywhere rests on the same particular Avonian bed, and the thinning of the Carboniferous Limestone (in places to the point of disappearance, so that the Cornbrook Sandstone rests upon Old Red Sandstone) is the result of simple overlap. In fact, neither of these conditions is satisfied: the Sandstone rests on different beds of the Limestone; and where the Limestone thins, the Lower Limestone Shales remain after the Oreton limestones have vanished. The evidence is best displayed in the ground east of Oreton, on the flanks of the Rea valley.

For about half a mile east of the Oreton quarries old workings show that the Oreton limestones which give rise to a high and steep scarp persist to a fair thickness; but towards the river valley the scarp falls to insignificance and the limestones diminish rapidly and are only a foot or two thick, at most, in outcrops 200 yds. west of Factory Cottages, where the Lower Limestone Shales are relatively well exposed. About 120 yds. north-west of Factory Cottages thin-bedded impure blue crinoidal limestones and shales of *Cleistopora*-Zone, only some 80 yds. from the outcrop of the Old Red Sandstone, are seen beneath a low scarp of conglomeratic Cornbrook Sandstone with plant remains. Across the valley, on the east side of the Rea, a slight retreat of the base of the Cornbrook Sandstone reveals about 10 ft. of pale-grey oolitic-crinoidal limestones like the Oreton limestones overlying highly fossiliferous Lower Limestone Shales seen in an old gravel pit. Farther east the Avonian outcrop narrows, and against the boundary fault it is possible that only the Lower Limestone Shales are present beneath the Sandstone. Although a clean contact with the limestones is nowhere seen at the base of the Sandstone, there is a suggestion, particularly in the outcrops north-west of Factory Cottages, that the dip of the Sandstone is appreciably less than that of the rocks beneath.

The map (Fig. 3) leaves no doubt that the relations can be explained only by unconformity with strong overstep.

Since the Cornbrook Sandstone itself underlies Coal Measures unconformably (Dixon, 1917, p. 1067), and the Coal Measures are known to belong to the Ammanian Series (Trueman, *in* Marshall, 1942, p. 24), the structural relations make the conclusion almost certain that the Sandstone cannot be Westphalian, but is Namurian in age, and bears the same relation to the Oreton limestones as its counterpart on Blorenge bears to the Oolite Group.

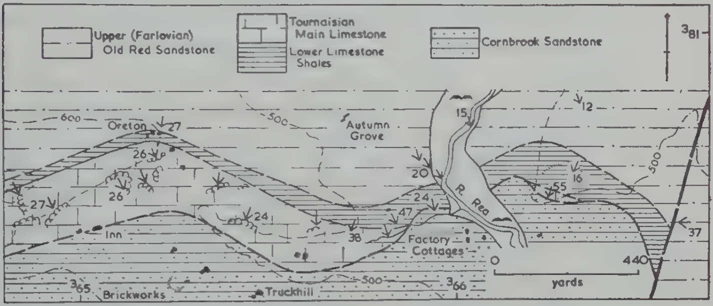

Fig. 3. Map of part of the northern outcrop of Carboniferous Limestone on Titterstone Clee Hill, to show overstep by the Cornbrook Sandstone

Incidentally, the highly improbable assumption that along the western border of the Titterstone outlier the Cornbrook Sandstone extends on to the Old Red Sandstone through simple overlap—overlap of the Lower Limestone Shales across the Farlow Sandstone, of the Oreton limestones across the Lower Limestone Shales, and of the Cornbrook Sandstone across the Oreton limestones—is obviated by this revised interpretation of the sequence.

In their lithological facies, and in their discordant junction, the Avonian and Namurian rocks of Titterstone thus closely parallel their lateral equivalents on the flanks of the Usk anticline to the south.

## 5. THE TITTERSTONE OUTLIER AND THE USK FOLD

### (a) The tilted flank of St. George's Land

In present-day outcrops it is vain to seek an extrapolated Usk axis in Shropshire, where the Carboniferous outliers of the Clee Hills are essentially synclinal in form, though partly owing their preservation to their altitude. The Old Red Sandstone of the plain of Hereford has mostly gentle dips except in the neighbourhood of the Woolhope anticline, and where the acuteness of the folding increases beyond Leominster, the trend is caledonoid and the fold axes are at best in echelon with the distant Usk axis.

Nevertheless, the stratigraphical links of the Titterstone outlier are with the rocks of South Wales and the Forest of Dean and the behaviour of the Namurian base mirrors that in Monmouthshire. Strongest overstep by the Cornbrook Sandstone occurs along the western margins of the outlier where no rocks of Avonian age are preserved and the Millstone Grit crosses Farlovian beds to rest on Lower Old Red Sandstone. The two narrow outcrops of Carboniferous Limestone emerge eastwards, and although there is an undulating contact between the series (as described in the neighbourhood of the Rea valley), dominant Namurian transgression is westward and the local sub-Namurian floor is as drawn in Fig. 1.

The regional relations may be interpreted as being due to an eastward intra-Carboniferous tilt of the order of several hundred (perhaps a thousand) feet in less than a mile, off a Namurian St. George's Land surfaced by Lower Old Red Sandstone. The pitch of the Usk fold near Abergavenny being southward, it has been concluded already (p. 301) that a wide expanse of Old Red Sandstone underlay Millstone Grit (actually or potentially) in east mid-Wales; and it is then not too far-fetched to regard the Titterstone rocks as lying on the east flank of the fold, in ground where the fold was little more than a vague swell more or less merged into the dome of St. George's Land—in contrast to its sharply-plicate form in Monmouthshire.

Supplementing the major Woolhope anticline, minor undulations doubtless affected the regional eastward sub-Namurian tilt in the ground between the Clee Hills and the Forest of Dean. The lines in Fig. 1 near Leominster are merely in simplest interpolation from north to south, and are wholly hypothetical. It is not impossible, or even improbable, that the Titterstone Tournaisian rocks occupied an isolated and independent structural basin in Namurian times only homologous and not confluent with the Dean Forest basin. Even so, the palaeogeographical reconstruction now put forward would not be overthrown, but merely modified, if more information on these undulations were available.

### (b) Relations with the Central Province

The present analysis throws little light on the relations of the South-Western Province with the Central Province. The contrasts in the Avonian succession between the Titterstone and the Little Wenlock and Lilleshall outcrops relate to diastrophic movements, pre-Visean and post-Namurian, of a different age and order from the Usk folding.

The long-held view that, in Tournaisian times, the northern margins of the South-Western Province lay a short distance north of the Clee Hills (see Wills, 1935, p. 223, fig. 27; Edmunds & Oakley, 1947, p. 28, fig. 6) is based on an unfounded assumption that present-day distribution of outcrops is a reflection of original distribution of sediments. Clearly this is not the case.

It is obvious that a tongue of the South-Western Province must have extended far beyond the Oreton outcrop. All Upper Palaeozoic strata of pre-Visean age are absent from north Shropshire, as in the more distant Oswestry country, the *Dibunophyllum* Zone at Little Wenlock and Lilleshall resting directly on a Silurian or a Cambrian foundation. Yet within a few miles marls and sandstones of the Lower Old Red Sandstone in normal succession reach a thickness of over 2000 ft. on the flanks of Brown Clee Hill beneath the unconformable base of the Coal Measures (Ball & Dineley, 1952), and it must be supposed that they, with an unknown thickness of overlying Farlovian and Tournaisian sediments, formerly extended northwards for an indefinite but considerable distance. The Downtonian outlier on Long Mountain adds supplementary evidence.

Since the major unconformity now to be seen at Little Wenlock and Oswestry lies beneath Visean strata, the regional relations imply that in mid-Avonian times the ground in mid-Shropshire had a southward tilt (as a component of a regional fall probably towards the south-east) of not less than 200 ft. per mile to allow a minimum thickness of 3000 ft. of Old Red Sandstone and Tournaisian Carboniferous Limestone to be completely obliterated by Visean overstep in the fifteen miles between Titterstone Clee Hill and Little Wenlock. Comparison with the sub-Visean unconformities in South Wales is strongly indicated.

Moreover, the sub-Namurian embayment of relatively thick Oreton limestones about Oreton itself, and the intensification of the overstep of the Cornbrook Sandstone eastwards to the Rea valley, offer a hint that the present-day synclinal form of the Titterstone outlier reflects a mid-Carboniferous structure with closure to the north—a downwarp complementary to the dome of St. George's Land and the Usk anticline to the west and south-west. Thus the present limits of Tournaisian outcrops are residual after Visean, Namurian, Westphalian, and post-Armorican erosion, and in themselves throw no light on Tournaisian palaeogeography. (See Fig. 4.)

There is no intrinsic reason why, in pre-Visean times, Old Red Sandstone and Lower Avonian rocks should not have formed a continuous belt of sediments around the northern flanks of St. George's Land from Shropshire into Anglesey (where a residual pocket of Lower Old Red Sandstone still remains). They may well have occupied a wide gulf, or even an extensive sea, joining the South-Western Province with the Central Province without the obstruction of any significant 'Midland Barrier' as

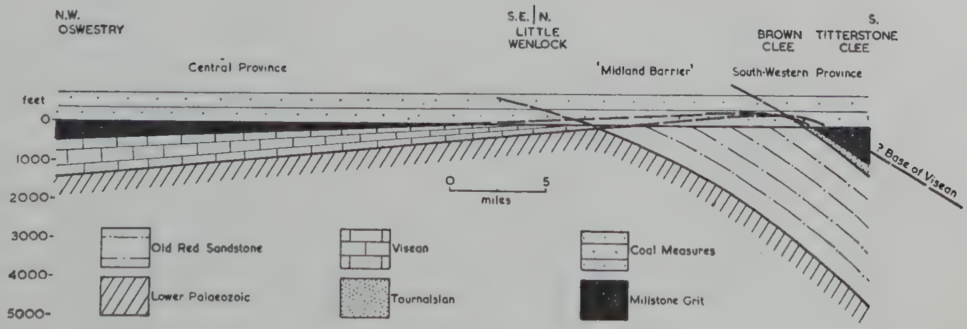

Fig. 4. Reconstructed section showing the inferred relations of the Upper Palaeozoic rocks between the South-Western and the Central Provinces in the neighbourhood of the Clee Hills in Westphalian times

a western outpost of the 'Mercian Highlands'—a barrier of which the evidence is almost exclusively Visean (compare Wills, 1951, pls. v, vi).

Along the south-western margins of the Central Province the Millstone Grit rests (as at Oswestry), or formerly rested (as, presumably, at Little Wenlock and Lilleshall), on high Visean strata, which it overstepped or overlapped completely in the ground towards Titterstone Clee Hill. The location of the corresponding zero isopachyte of the *Dibunophyllum* Zone is not now precisely identifiable, owing to Westphalian overstep. It is inserted speculatively in Fig. 1, merely to suggest a possible northward swing around the (? Carboniferous) high ground of the Long Mountain and the Longmynd, and to delineate the certainty that it must lie between the outcrops at Oswestry and Little Wenlock on the one hand and the Titterstone outlier on the other. The line does not provide, nor can it convincingly be made to provide, any hint of a northward extension into the Central Province of the Namurian Usk anticline.

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## DISCUSSION

PROFESSOR A. H. COX exhibited a Geological Survey map on which he had marked the axis of the Usk Anticline from the Usk Inlier to the area about five miles north of Cardiff.

The axis could be seen to swing gradually from north–south in the Usk Inlier to west-south-west in the area north of Cardiff. He had been unable to trace the fold farther south and west owing to the extensive sheets of outwash gravels from the drift.

He did not think that the Usk axis had any direct connection with the Cardiff–Cowbridge anticline.

MR. T. R. OWEN congratulated Professor George on yet another notable contribution to our knowledge of Carboniferous palaeogeography.

Mr. D. G. Jones and the speaker had recently been studying the Millstone Grit–Carboniferous Limestone junction along the North Crop of the South Wales Coalfield between Glynneath and Brynmawr. As Professor George had described, the basal beds of the Millstone Grit rest on $D_3$ and $D_2$ limestones in the west and on $S_2$ limestones in the east of this area. The actual junction of Millstone Grit and Limestone is frequently obscured by scree and boulders, but in some scattered localities the contact can be examined. At these exposures, the junction is of a more gradational character than one associates with a simple, though major, unconformity. Near Glynneath and Ystradfellte, the lowest conglomerates often appear 'to grade down into $D_2$ limestones which, near the contact, contain grading pockets of pebbly grit and scattered, large quartz pebbles'. North of Dowlais, the Basal Grits grade down into $D_1$ oolite and, moreover, $D_1$ fossils occur within the lowest pebbly and partly calcareous grits. Near Tredegar and Brynmawr, there are examples of gradation from dolomitised or silicified $S_2$ limestones into the lowest beds of the Millstone Grit.

In view of these peculiarities and also of the sandy character of higher Avonian zones in the Forest of Dean, the speaker suggests that the uplift of the Usk area, and of areas to the north, began before Namurian times—possibly as early as $S_2$ times.

Professor George had clearly demonstrated the overstep at the base of the Cornbrook Sandstone on Titterstone Clee. Was it not possible, however, that sandy deposition, following uplift, had begun in this area also before Namurian times? The great thickness of the Millstone Grit in this region was puzzling in view of the marked thinning of this formation towards the north-eastern corner of the South Wales Coalfield and the absence of Millstone Grit in the Forest of Dean.

DR. R. K. BLUNDELL thanked Professor George for another masterly exposition of Carboniferous geology. The importance of the Usk axis as a control on Carboniferous sedimentation and structure was now becoming increasingly evident, and Professor George's work was a major step forward in the elucidation of the structural evolution of this fold-belt.

It would appear that the Usk axis may also have been associated with igneous activity, albeit on a very small scale. The monchiquite which occurs between Usk and Chepstow appears to represent part of an infilled vent. The infilling consists largely of blocks of Old Red Sandstone rocks but, since the original discovery by R. A. Criddle in 1952, fragments of Carboniferous Limestone are found to be not uncommon. The apparent absence of Upper Carboniferous rock types might thus be interpreted as indicating that the volcano was active in pre-Namurian times.

All the recognisable limestone fragments, some of which are poorly fossiliferous, seem to be Tournaisian rather than Visean. Might this, therefore, suggest that the Usk axis showed earlier signs of restlessness in mid-Avonian times?

PROFESSOR GEORGE, in replying, said that the uncertain position of structural axes, referred to by both Professor Cox and Dr. Robertson, was not to be overlooked; and the author's map of the sub-Namurian floor was a reconstruction and not a record. It was true that the Hercynian Cardiff–Cowbridge anticlinal crest was 'lost' west of Cardiff under both Trias and drift, and its precise course could not be exactly determined. Probably the crest itself was multiple in the neighbourhood of Cowbridge, with minor folds in echelon on its flanks. Nevertheless, the broad anticlinal form was marked out fairly clearly by the outcrop of the top of the Old Red Sandstone and by the regional dips, and the pitching nose of the earlier Namurian anticline could well be placed approximately in the main axial zone of the existing fold. No theory of causal links between Namurian and post-Carboniferous folding was put forward, though the coincidence of axial position suggested that the later movements intensified structures already blocked out, if not defined in detail. The reconstructed map did not have equal strength in all its parts, and here and there alternative arrangements of its lines would be equally valid no doubt, but the essential Namurian topography it delineated was to be accepted, whatever local modifications might be called for.

The very peculiar rock types to which Mr. Owen drew attention required a revised interpretation of the nature of the Namurian–Avonian junction. They showed an admixture of grits and conglomerates with crinoidal limestones and oolites that rarely gave the appearance of a clear-cut planar Namurian transgression across Visean zones but often suggested a gradual upward passage from the calcareous into the arenaceous sediments, no matter what the age of the topmost limestones might be. Nevertheless, any new interpretation was likely to be lithological rather than stratigraphical. It was difficult to suppose that a thin bed of gravel, unlike any known elsewhere in South Wales, violently diachronous from $D_3$ in the Neath valley to mid-$S_2$ in the Clydach valley, and carrying terrigenous detritus indistinguishable from that of the true Millstone Grit, should descend in horizon from zone to zone in almost precise parallelism with the overlying transgressive Namurian, with which it was everywhere in contact and from which it was rarely, if ever, to be distinguished. Analogy with the Drybrook Sandstone was not close, since the progressively increasing sandiness of the Drybrook Limestone northwards took place by lateral passage with interlayering of sandstones and limestones. Apart from Mr. Owen's hypothesis, in the zones preserved there was no hint of Visean movement along the Usk line, though the evidence remaining was tenuous and did not exclude the possibility. In any event, the conjectural existence of an earlier arch did not affect the form of the arch in Namurian times, and the reconstructed map put forward would not be significantly altered by an antecedent Visean structure.

The age of the Cornbrook Sandstone had not been settled by conclusive fossil evidence. Conceivably it might be Visean, but the rock was very different from the nearest Visean occurrences at Little Wenlock and Lilleshall, and compared most closely with the Millstone Grit of the Oswestry district. It found its place on Titterstone Clee Hill as an upper member of a series showing progressive overlap (and overstep) southwards (see Fig. 4).

Mr. Archer's doubts about the connection of the Titterstone structure with the Usk anticline were apposite. The Clees at the present day were synclinal, with caledonoid trend, along a line divergent from the Usk line. Their connection with the southern outcrops could only be indirect, and intervening contemporaneous Namurian flexures along the Woolhope axis might well have been strong. There was no remaining indication in the Hereford–Leominster ground of what the Namurian floor might have been like and the reconstructed map was less conjectural than allusive in linking the Titterstone outcrops with those to the south by a line that was merely the simplest where any other would be fanciful. That there was a link, both stratigraphical and structural, was nevertheless a theme of the paper.

Dr. Blundell's reference to the presence of Carboniferous inclusions in the Usk monchiquite was exceedingly interesting but, not having seen the evidence, the author could say little of their possible relevance to an interpretation of Namurian palaeogeography. Presumably they owed their position to incorporation from a roof or a vent wall. That they should appear to be exclusively Tournaisian might follow from the absence of higher beds in the roof at the time of intrusion due (perhaps in combination) to Tournaisian injection (conceivably with accompanying Usk folding), or to post-Hercynian erosion (implying a post-Carboniferous age for the dyke), or to Westphalian overstep, or to Namurian overstep. If the last, then it indicated westward extinction of Visean rocks even more rapidly than was shown on the author's map.

# Field Meeting at Brentwood and South Weald, Essex

**15 May 1954**

Report by the Director: F. A. MIDDLEMISS

Received 4 November 1954

THIRTY-FIVE MEMBERS and friends met at Brentwood Station at 2.20 p.m. and, by kind permission of Messrs. Beautility Furniture Ltd., visited the old Brentwood Brick Pit. At one time this was the best section of Eocene strata in Essex. It has been visited by the Association on three previous occasions: in 1889, 1915 and 1923 (Herries *et al.*, 1889; Boswell, 1915; Berdinner, 1925). It will not be accessible in the future as the present owners intend to erect a new factory upon its site. The process of filling the pit was well advanced on the occasion of this visit and although little of the section remained, the typical lithologies of the Claygate and Bagshot Beds (Berdinner, 1925) could be examined and poorly-preserved lamellibranchs were collected from London Clay septaria lying on a tip heap.

It may be of interest to place on record the succession measured by the Director in this pit in 1949:

| | | |
|---|---|---|
| PLEISTOCENE | Sludged gravel or old boulder clay ... ... ... | 6 ft. |
| BAGSHOT BEDS 12 ft. | Compact and rather massive very fine red-buff sand ... | 6–8 ft. |
| | Buff sand with iron-stained layers, ferruginous concretions, small faults (throw half in.), small-scale current bedding; flecked with small, irregular patches of black limonite ... ... ... ... | 5 ft. |
| CLAYGATE BEDS 33 ft. | Fine sands with seams of chocolate-coloured clay, iron-stained layers and ferruginous box-stones containing white sand. Small-scale current bedding in places in sandy layers ... ... ... ... | 3–4 ft. |
| | Variegated intermixture of dark lilac-coloured clay and brown sand ... ... ... ... ... | 18 ft. |
| | Dark variegated clayey loam ... ... ... | 12 ft. |
| | Junction obscured | |
| LONDON CLAY | in lowest, waterlogged part of pit. Heaps of fossiliferous septaria. | |

Next the party walked towards Brentwood town and noted the incoming of gravel overlying Bagshot Sands at Brentwood Hill, near the Police Station. The Director stated that, although no gravel was shown underlying Brentwood on the Geological Survey map, there were, in fact, several feet of it covering the highest ground. The edge of the gravel sheet occurs throughout the area at about 320 ft. O.D., and is often marked by a distinct break of slope. The centre of the town stands upon a second and higher gravel-covered level at a little over 350 ft. O.D., the 320 ft.-level being less well developed here than in the Langton's area which was seen later in the afternoon. The London road between Brentwood Hill and Brook Street Hill runs along a strikingly bevelled spur at just over 270 ft. O.D., which must represent part of an erosion-level, occurring some 15 ft. above the base of the Bagshot Beds.

After walking along the main road to Brook Street, the party made its way to the village of South Weald, a smaller replica of Brentwood in its geological situation. Tea was enjoyed in the garden of the Tower Arms.

In the evening the party moved across Weald Park to the old gravel pits at Langton's which, although now much obscured, still show the Bagshot Pebble Bed overlain by gravel. The former is now seen most clearly in the pit on the west of the road, and the latter in the pit on the east side of the road (Woodward, 1889; Dewey, 1924). Wooldridge regarded the Bagshot Pebble Bed as the remains of an offshore pebble shoal of considerable extent (Wooldridge, 1924). The Director's mapping does not support the view that this pebbly facies is more than local, existing in a series of scattered patches suggesting an irregular group of small shingle banks rather than one large continuous shoal.

In the pit on the east side of the road at Langton's, the 320 ft. gravel was seen to consist mainly of brown and yellow rounded flints with a large proportion of angular flints, numerous pieces of vein quartz and occasional pebbles of grey-brown quartzite. It is probable that these are glacial outwash gravels and are distinctly younger than those of Warley. The tendency of the pebbles to vertical alignment, as previously recorded, was observed.

Other signs of glaciation were pointed out, notably certain scattered deposits of gravel and sand which the Director regarded as head. At the top of the Brentwood Brick Pit there was a good section in sludge gravel in 1949. This is a densely packed mass of pebbles, including angular fragments, which appears to be derived from the gravel lying about 40 ft. higher up the hill. The matrix is a very fine loam or brickearth, with patches and lenticles of clay showing small contortions. In places this deposit occupies channels in the Bagshot Sand. The differences between this and the pebble gravel and its outwashed derivatives are that the pebbles are more closely packed in the head and that the matrix of the gravel is a fine brown sand rather than the loamy brickearth-like material, with clay, found in the head. A possible alternative view of this deposit is that it is an old boulder clay.

Several small outliers of Bagshot Sand, occurring well below its true level around and just north and east of Weald Park, are regarded as 'sandy head'. One of these was seen at a locality (572943) in the middle of Weald Park. Much of the ground at about 250 ft. O.D. has a thin (1 ft. 6 in.) 'smearing' of residual decalcified boulder clay, a loamy material with minute angular flint and quartz fragments and larger pebbles, which was seen between Brook Street and South Weald. This material is particularly confusing in connection with mapping where, as here, it overlies London Clay. Further, the difficulties consequent upon the frequent occurrence of residual boulder clay and of gravelly and sandy outwash may account for the repetition of 'brickearth or loam' not only at the top of the Bagshot Beds but also 50 ft. down in the London Clay in the General Section given by Woodward (1889).

Finally the party walked across the fields and through a corner of High Wood, crossing the major watershed between the Thames and East Coast drainage systems, and came out on to the Ongar Road. Here the Director summed up the general physiography of the area and contrasted the rather featureless boulder clay country visible to the north-east with the undulating country traversed earlier in the afternoon, south-west of the main watershed. The valleys of the streams flowing to the Thames are much deeper and more strongly marked than those of the streams flowing to the Chelmer. Features due to the interaction of lithology and denudation, such as changes in slope, are much more obvious on the Thames side. Also the mantle of boulder clay has been removed almost entirely, except for some residual matter, on the Thames side, whereas large spreads of boulder clay blanket the surface on the Chelmer side. Thus, erosion is more active by the Thames streams, although why this should be is not clear.

The President moved a vote of thanks to the Director, after which the party dispersed.

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# Field Meeting in the Kidderminster Area

**22 August 1954**

Report by the Directors: W. WALDRON and G. COTTON

Received 8 January 1955

THE FIELD MEETING was arranged to enable members to examine the Bunter in the Kidderminster–Habberley area, and the Dittonian and Downtonian in the Trimpley inlier.

First, the quarry in the Upper Mottled Sandstone at Aggborough (National Grid Reference 834753) was visited. It was this locality which yielded one of the few fossil fish ever recorded from the Bunter of this country. The specimen, identified by Dr. E. I. White as a Perleidid, was collected by Mr. Whitehouse who indicated to the party the exact spot in the quarry where he made his discovery. A further search failed to reveal any additional fossils. A deposit of dune sand, ten feet in thickness, with characteristic bedding was seen in the more northerly quarry.

Next the party examined the base of the Pebble Beds and Basal Breccia at Lea Bank (811760), and the Dune Sand at Devils Spittleful (807747) and Habberley Valley. The last locality is very near to the southward extension of the Enville fault, the position of which was approximately fixed by the identification of Enville Breccia on the western side of the valley.

The party then proceeded to the Trimpley inlier where a small quarry was examined at Whitnells End (797817) in the basaltic sill intruded into the Kinlet Beds. The basalt shows characteristic spheroidal weathering.

A short distance to the east, the Downtonian marls, the oldest strata in the inlier, were seen and at Shatterford (799804), the Dittonian sandstone, which forms the core of a syncline, was examined.

Finally, the party inspected a roadside exposure (805798) to the west of the Enville fault. The section showed clearly the fault separating the Bunter Pebble Beds from a small area of Enville Breccia.

A vote of thanks to the Directors of the field meeting was proposed by Mr. Aiers.

# Easter Field Meeting in the Birmingham District

## 16–19 April 1954

Report by the Directors: F. W. SHOTTON, E. D. LACY
and I. STRACHAN

Received 30 March 1955

THE HEADQUARTERS for the meeting was Carey Hall, Selly Oak, Birmingham.

### Friday, 16 April

The excursion commenced with the well-known Rubery Section. The Lower Cambrian Lickey Quartzite was seen to dip gently to the east, intruded by a greatly rotted dyke, possibly of Ordovician date, and to be overlain by the Rubery Sandstone and Rubery Shale with fossils of Upper Llandovery age. The unconformity, which is great in terms of time, is manifested chiefly in terms of an irregular junction, with pebbles lying in the hollows, and by sandstone dykes extending down into the underlying Cambrian.

The remainder of the day was spent on the New Red and glacial sequence of the Bromsgrove area, with the following special places of call:

*Sling Common Gravel Pit*, *Romsley*. An exposure was examined in the lowermost sixty feet of the coarse gravel forming the bottom of the Bunter Pebble Beds, which is faulted against Clent Breccia. Here the party was joined by Professor L. J. Wills, and later took lunch at his house, nearby, where he had collected some of the largest of the far-travelled Bunter pebbles, including a fine quartzite eighteen inches in length.

*Money Lane Pit*, *Wildmoor*. Here a contrast was seen between the bright red marly sands of the Upper Bunter Moulding Sand Group and the overlying drift of sand and gravel, with pebbles mainly from the Bunter, but also including Welsh and Shropshire rocks. The glacial sequence is 'Old Drift' and now formed a hill capping, apparently demonstrating the sequence due to a glacier advancing over its own outwash plain—an upward succession of sand, gravel and boulder clay.

*New Wildmoor Boring*. By courtesy of the East Worcestershire Waterworks Company, the party was able to inspect over 800 ft. of continuous core showing all the Upper Bunter and all but the last few feet of the Middle Bunter, and also to witness the extraction of a length of core, three feet in diameter, from the second borehole being sunk at the time.

*Bromsgrove Lanes.* Roadside sections showed the Upper Bunter and the Keuper Sandstone, including the basal conglomerate of the latter with its large fragments of fresh orthoclase from an unknown igneous source.

'*Scorpion Quarry*', *Bromsgrove*. This is the classic site, now scheduled as of scientific importance, where Professor L. J. Wills obtained a considerable flora and fauna, including the arachnid *Mesophonus*, from certain clay lenses (Wills, 1910). It is not now worked, but a number of plants, probably mainly *Schizoneura*, were collected.

### Saturday, 17 April

Leaving Carey Hall, the party proceeded by bus across part of the South Staffordshire Coalfield, noticing the outcrops of Calcareous Conglomerate and Etruria Marl on the Birmingham–Wolverhampton road as well as the heights formed by the Rowley Regis dolerite and the Silurian of Dudley Castle. After reaching the Wren's Nest Hill, the party walked round the southern end of the hill to see the periclinal nature of the inlier and collect a large number of the characteristic Silurian fossils from the Nodular Beds of the Wenlock. Also the old workings in the limestone were examined because the limestone pillars in the underground working show the rapid variation in the purer limestone from unbedded 'crogballs' to bedded limestone. The return to the bus was made across the hill, to see the hollow made by the softer Wenlock Shales which occupy the centre of the pericline.

From the Wren's Nest the party travelled westwards to Gornal, to see the Gornal Sandstone and the associated Downtonian beds. Only a few fish fragments were found in the sandstone of Rollason's Quarry, however, but the underlying shales yielded eurypterid and plant remains. North of Ellowes Hall the Red Downtonian was seen in a stream section and farther west, across the Boundary Fault, Coal Measure beds were seen. Proceeding southwards to Turner's Hill, the party found fragments of Upper Ludlow beds with *Chonetes striatellus* and also the outcrop of Sedgley Limestone showing the bone bed described by H. W. Ball (1951, p. 228). Good specimens of the bone bed were obtained. The return journey was made by essentially the same route as the outward journey.

### Sunday, 18 April

This day was spent at the north end of the Warwickshire Coalfield. The first pit was that of Stoneware, Ltd., east of Dosthill, where the steep upturning of the beds allows the inspection of all seams of the Middle Coal Measures from the Seven-Feet upwards, into the base of the Etruria Marl. In the adjacent pit of the Kingsbury Brick and Tile Company were seen the greater part of the Etruria Marl, with espley breccias composed chiefly of Stockingford Shale fragments, overlain by the basal part of the Halesowen Sandstone.

The remainder of the day was spent mainly on the sub-Carboniferous foundation of the coalfield. At Boon's Windmill Hill Quarry, Nuneaton, the Pre-Cambrian shows varied aspects—dolerite of the Blue Hole, coarse quartzo-felspathic ashes, and markfieldite. The latter forms a very irregular surface—an old shore line—beneath the unconformity of the Cambrian (Hartshill) Quartzite, and the main part of the quarry is in the Park Hill and Tuttle Hill divisions of this group. These are penetrated by numerous sills of camptonite.

The Midland Quarry, Nuneaton, has a remarkable variety. Into the thin-bedded quartzites of the Tuttle Hill division is intruded a massive camptonite sill which is itself cut by a wide dyke of similar material. Upon all these the Keuper Sandstone rests with strong unconformity. The highest overburden of the quarry is composed of red flint-bearing bedded clays, a product of Glacial Lake Harrison.

The last pit to be visited was the well-known Woodlands Quarry, a scheduled section of scientific importance. Red Purley Shales of the Stockingford Group rest upon the Camp Hill quartzites and sandstones of the Lower Cambrian. Near the top of the Camp Hill group is the red Hyolithes limestone, the lowest fossiliferous horizon in the Midlands. Specimens of *Hyolithes* and *Coleoloides* and rare brachiopods were found by the party.

### Monday, 19 April

After leaving Carey Hall the first stop was made to study the Calcareous Conglomerate of the Enville Group, exposed in a shallow cutting on the New Wolverhampton Road. Several feet of the conglomerate were seen to dip about 20° SE. Predominating were well-rounded pebbles of Carboniferous chert and limestone, averaging two inches in diameter. The cement was calcareous and the jointing seen to cut across the pebbles.

At Newbury Lane, Oldbury, in a disused brick pit on the eastern side of the Wolverhampton Road, the party was able to observe from a vantage point the very rapid lateral variation of a prominent band of 'espley' in Etruria Marl from a thickness of ten feet down to one or two feet in the space of fifty to sixty yards. In Messrs. Pratt's New Century Brickworks the mottled red and green marl was examined. Here again 'espley' conglomerate of very variable thickness occurs, the pebbles consisting almost entirely of fine-grained basic igneous rock.

Nearby is situated Pugh's quarry of Tarmac Ltd., which was worked until very recently for 'Rowley Rag' (olivine dolerite). Although partly flooded on its western side, the quarry shows the lower contact between the Etruria Marl and the igneous mass. This contact ascends 'stepwise' to the west. The chilled edge of the dolerite is decomposed and the contact effects are negligible. The upper parts of the quarry afford excellent examples of spheroidal weathering and the columnar dolerite below the main bench is considerably weathered down to water level, at least sixty feet below the original surface of the hill.

From the eastern side of the Rowley intrusion the party crossed by coach to the western side. Here, in the Hailstone Quarry of the Rowley Regis Granite Co., the boundary of the igneous rock with the Etruria Marl has been exposed at a number of places recently.[1] The exposures reveal a progressive easterly swing of the contact, which dips steeply to the north-east, over a distance of some 150 yds. as it is followed south-eastwards. The junction does not offer evidence of tectonic disturbance and a good chilled edge is to be seen. Again the baking effects in the marl are slight. Well away from the contact columnar structure is strongly developed. The igneous rock looks very fresh and unweathered.

It is clear that the evidence afforded by these two quarries does not support a 'text-book laccolite' interpretation of the Rowley intrusion.

The excursion finished with a visit to Darby's Hill Quarry, situated in the centre of the mass, where almost the whole thickness (about 200 ft.) of the Rowley dolerite is visible. The bottom contact is now obscured, but the top one was gained, after a scramble, when it was found to be horizontal, with the usual chilled edge and to have produced feeble baking of the marl. From this high point a fine view over the Black Country to Barr Beacon was obtained.

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[1] The existence and character of these exposures was brought to the notice of the present writer by W. G. Hardie, Department of Geology, University of Birmingham.

# Field Meeting at Charlton and Bostall Heath

**21 May 1955**

Report by the Director: F. J. EPPS

Received 27 May 1955

THE PRESIDENT and a party of twenty members met at Charlton Station and, proceeding to Valley Grove, examined the junction of the Upper Chalk with the Eocene (Thanet Sand). The sand-pit in Maryon Park (Gilbert's Pit) was then visited where the succession to be seen is:

| | | |
|---|---|---|
| YPRESIAN | Blackheath Beds | marine |
| UPPER LANDENIAN | Striped Loams | estuarine and freshwater |
| | Woolwich Shell Bed | |
| LOWER LANDENIAN | Woolwich Bottom Bed | marine |
| | Thanet Sand | |

The Upper Chalk, formerly seen, is now covered with debris. The Eocene Series rests conformably upon the Cretaceous, although this becomes apparent only by a study of the zones of the Chalk which are covered over a large area. The great break between the Chalk and the Eocene is marked by a complete change in the fauna and lithology. The large reptiles and cephalopoda of the Secondary rocks, with many of the echinoderms and deep sea siliceous sponges, have disappeared. Tropical and sub-tropical plants and many vertebrates, including mammals, make their appearance.

The Thanet Sand, about 45 ft. in thickness, is a fine sand, with grain-size 0.1 to 1 mm., 95 per cent of which is $SiO_2$. Among the fairly abundant detrital minerals present are ilmenite, limonite, zircon and rutile, while tourmaline, staurolite, andalusite and muscovite also occur. Casts of *Pholadomya* are the only fossils recorded from the Thanet Sand of Charlton. The sand at the base is in every way suitable for moulding, and its presence in the area may have led to the selection of Woolwich as a site for the Arsenal. The uppermost part has been worked for the manufacture of rough, green bottle glass. The Thanet Sand meets the bed of the river at Charlton and a large proportion of the water for the wells of London may enter directly from the Thames at this point.

The Woolwich Beds are the equivalents of the Reading Beds, the names serving to differentiate between their respective conditions of deposition. The fauna reveals that in East Kent they are of marine origin, but that at Woolwich, and in the surrounding area, brackish water conditions existed, while in the Reading district the beds are of freshwater origin. The Woolwich Beds may be divided into (1) The Bottom Bed, (2) The Shell Beds, and (3) The Striped Loams.

The junction of the Bottom Bed with the Thanet Sand is usually marked by a pebble bed about one foot in thickness. The pebbles are of flint and perfectly rounded, their smaller size helping to differentiate them from the pebbles of the Blackheath Beds. Probably they are the remnants of flints derived from the Chalk which were exposed to the action of the sea at the northern base of Wealden anticline. Above the pebble bed is a coarse, greenish glauconitic sand which, together with the fossil assemblage (*Glycimeris terebratularis*, *Corbula* and *Lamna* teeth), denotes the marine character of the bed. This bed passes upwards into a finer sand with less glauconite. It is likely that the change was caused by the silting up of a great river mouth and shows the transitional stage between the prevailing marine and lagoonal conditions that followed. The maximum thickness of the Bottom Bed is 25 ft.

The Shell Beds consist of shells of brackish-water forms occurring in laminated clays. Usually there is an *Ostrea* Bed between two others which are chiefly composed of *Cyrena*. Occasionally a bed occurs containing freshwater fossils only (*Vivaparus* and *Unio*). The Shell Beds reach a thickness of 30 ft. and are the equivalent of the Reading Mottled Clays with which they are interstratified in some areas.

The Striped Loams consist of stratified beds of sand, loam and clay, varying in colour from red to green and reaching a thickness of 25 ft. The included mollusca are *Ostrea*, *Cyrena*, *Melania*, *Cerithium* and *Hydrobia*, while leaves and seeds of dicotyledonous plants, pointing to a temperate climate, have been found. The Woolwich Beds are not of great economic value; occasionally bricks are made from some of the material, but they provide good soil for crops and orchards. At the end of the Landenian Period earth movements occurred which caused the area occupied by the Woolwich Beds to sink and allow encroachment by the Ypresian sea in which the Blackheath Beds, seen at the uppermost part of the section, were deposited.

Next, the party proceeded to the Cemetery Pit in the East Wickham Valley at King's Highway, Plumstead. This showed a similar section to that at Charlton, the freshness of the face now being worked enabling features to be seen which are obscured at Charlton. A remnant remains of Pleistocene deposits of Taplow Terrace age. These beds, originally 30 ft. in thickness, have yielded many mammalian bones, including those of bear, bison, horse, mammoth, rhinoceros and musk ox.

The slipping of masses of London Clay from the Shooters Hill area to the river hill slope at Bostall Heath, before the formation of the East Wickham Valley, was discussed. A traverse was made of the plateau of Blackheath Beds to study the relationship of the spurs and coombes with the geological formations. Water percolating through the Blackheath Beds is arrested by an impervious clay in the Woolwich Beds and solution hollows are formed by the washing out of sandy material. Collapse of the pebble bed follows and a small stream continues the formation of the coombe.

The site of the 'outlier' of London Clay was seen on Bostall Heath. The mass of clay, 8 ft. in thickness, which, in the Director's opinion was part of the hill slip from Shooters Hill, as previously mentioned, was removed when the site was levelled in 1920. London Clay fossils were noticed in the foundations of 'Shornells', and the Pine Pool in Lessness Wood is held in a pocket of the clay. As further examples of this slipping, traces of Plateau Gravel from the 400-ft. platform on Shooters Hill have been noticed at 230 ft. O.D., in Lessness Wood.

Next the Blackheath Shell Bed in Lessness Abbey Wood was examined. This bed was deposited at the mouth of a gigantic river which flowed from the west, aided by numerous subsidiary streams from the north. A gradual sinking of the basin permitted the flooding of the low-lying coastal flats by a transgressing sea, thereby giving rise to lagoonal conditions which passed gradually into a seaward phase in the east and the Blackheath pebbles may have formed banked shoals at the mouth of the river. Later earth movements caused further sinking, with a consequent inrush of the sea from the east. Thus a marine fauna would first mingle with the brackish type and eventually become dominant. Some forty species of mollusca have been collected from the site in Lessness Abbey Wood, including many new records from this horizon. Other remains include corals, bryozoa, crabs, numerous species of fish, crocodiles, turtles and the mammals *Hyracotherium*, *Protoadapsis* and *Coryphodon*.

The visit concluded with an inspection of the Lessness Abbey ruins and the excavations in progress. The President, Dr. L. R. Cox, thanked the Director, on behalf of the party, for his services. The Association records its indebtedness to the Chief Officer, Parks Department of the London County Council and to Messrs. Saunders Transport Ltd. for courtesies extended and for permission to visit the pits concerned.

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# Summer Field Meeting in Italy

**16–29 September 1954**

Report by the Excursion Secretary: D. V. AGER
Director: A. Azzaroli, University of Florence

Received 30 June 1955

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## 1. INTRODUCTION

TWENTY-FIVE MEMBERS of the Geologists' Association gathered in Florence on the evening of 16 September 1954. There they were met by Dr. A. Azzaroli, of the University of Florence, who spent the next nine days showing them the geology of the North Apennines. Afterwards the majority of the party went southwards to pay a brief visit to the Naples area.

In recent years the structure and sedimentation of the North Apennines has been studied in great detail by a group of Italian geologists headed by the late Professor C. I. Migliorini and Professor G. Merla. Potentially their remarkable findings are of world-wide application. Unfortunately, apart from one paper by Migliorini (1952) and a review by Maxwell (1953), there is no literature in English on this important work. It seems desirable, therefore, to summarise here the chief findings and hypotheses of the recent workers in this area. A full bibliography of publications on the North Apennines (in Italian, with an English summary) is to be found in Merla's important 1952 paper.

## 2. OUTLINE OF THE GEOLOGY OF THE NORTH APENNINES

The general succession in the North Apennines is as follows (mainly after Maxwell, 1953):

PARAUTOCHTHONOUS TO AUTOCHTHONOUS (partly moved or unmoved)
- QUATERNARY—alluvium, travertine, moraines, etc.
- PLIOCENE AND EARLY PLEISTOCENE—lake deposits.
- UPPER MIOCENE AND PLIOCENE—marine sandstones, marly shales, gypsiferous clays.
- OLIGOCENE AND MIOCENE—*Loiano* formation: conglomerates, molasse, etc.

| | |
|---|---|
| ALLOCHTHONOUS<br>(moved over considerable distances) | JURASSIC TO OLIGOCENE—*Argille scagliose* ('scaly clays'), including exotics such as 'greenstones' (Jurassic), *Pietraforte* sandstone (Cretaceous), *Alberesi* limestone (Eocene), etc. |
| AUTOCHTHONOUS<br>(unmoved) | LOWER AND MIDDLE MIOCENE—greywacke sandstones and shales—*Marnoso-arenacea* formation and *Serie di Vicchio*—about 2000 metres.<br>OLIGOCENE AND BASAL MIOCENE—greywacke sandstones and shales—*Macigno*—up to 3000 metres.<br>CRETACEOUS TO OLIGOCENE—varicoloured shales—*Scisti policromi* (or *Scaglia*), with brecciated limestone (*Brecciole nummulitiche*) at top. 50–450 metres.<br>UPPER JURASSIC TO LOWER CRETACEOUS—thin-bedded chert (*Diaspri*) and siliceous limestones; thin-bedded cherty limestone (*Neocomiano*). 20–350 metres.<br>LOWER AND MIDDLE JURASSIC—massive limestone (below) and bedded limestone with chert (above). 500–1000 metres.<br>UPPER TRIASSIC (including RHAETIC)—dark limestones, anhydrite and dolomite, altered near surface to leached and re-crystallised breccia (*Calcare cavernoso*); massive dolomite (*Grezzoni*). About 500 metres.<br>PERMO-CARBONIFEROUS—schists, phyllites, quartzites and conglomerate (*Verrucano*), altered rhyolite. |

The oldest rocks known in the northern Apennines are of uppermost Palaeozoic age, with rare fossils (mainly plants) and usually metamorphosed more or less. The highest of these rocks is a distinctive pebbly grit or conglomerate—the *Verrucano*—which appears to have been deposited when the Palaeozoic Tethys was reduced to its minimum extent. The *Verrucano* is always taken as marking the top of the Palaeozoic.

Mesozoic sedimentation began in the region from a shallow transgressive Upper Triassic (Noric) sea. A basal quartz grit rests unconformably on the Palaeozoic rocks, and is followed by a thick calcareous series with rare marine fossils such as the gastropod *Worthenia escheri* (Stoppani) and the Rhaetic lamellibranch *Pteria contorta* (Portlock). The most remarkable of the Triassic deposits is the *Calcare cavernoso*, which is thought to have originated as a series of alternations of dolomite and anhydrite in a shallow, evaporating sea. Near the surface the anhydrite has been hydrated to gypsum, which has been dissolved nearly everywhere, with the production of a collapse breccia. This last has been re-cemented subsequently.

There appears to have been continuous sedimentation from above the unconformity marking the beginning of the Trias, throughout the Mesozoic of this region until the end of the Oligocene. No acceptable breaks have been detected in this succession, with a single doubtful exception below the *Macigno* near Spezia. Many breaks have been described in the past, but these are now regarded as purely tectonic.

Above the Triassic rocks of the Apennine autochthon come massive limestones of the Lower Lias (Hettangian and Sinemurian). These are thought to have been deposited in relatively shallow seas, though fossils are scarce and local. In the Alpi Aquane they have been metamorphosed to give the famous white Carrara marble.

Nearly everywhere the Middle and Upper Lias and the Middle Jurassic beds (or 'Dogger') of the North Apennines consist of well-bedded limestones with frequent chert nodules. Probably these were laid down in somewhat deeper water. The Upper Jurassic radiolarian cherts (*Diaspri*) and the variegated beds of Cretaceous to Oligocene age (*Scaglia*) which followed, may have been deposited at bathyal depths.

Throughout this considerable period (Triassic to Oligocene), the general rarity of preservable organisms, and the remarkable constancy of lithological facies, contrast markedly with the state of affairs represented in the British succession. The thinness of the pre-Oligocene rocks in the autochthon is also noteworthy, both in comparison with rocks of the same age elsewhere, and in contrast with the very thick sedimentation that followed.

The *Brecciole nummulitiche*, at the top of the *Scaglia*, marks the beginning of this sudden change in sedimentation, with the incoming of coarse greywackes often in thick graded beds. The sudden flow of terrigenous material initiated in the *Brecciole* continued in the *Macigno* of the Oligocene and Lower Miocene and was concluded in the east by the *Marnoso-arenacea*. The *Macigno* type of sedimentation has been attributed by Kuenen & Migliorini (1950) to the action of turbidity currents. Each of the thick graded beds is thought to be the deposit of one such current.

A major land-mass, west of the present coastline, is postulated as the source of the Mesozoic and early Tertiary sediments of the Apennines. This land-mass subsided in Quaternary times and is now largely, if not entirely, covered by the Tyrrhenian Sea. A possible remnant is preserved in the island of Elba.

The main orogeny of the Apennines began during the Oligocene period and continued until as late as the Pleistocene. During this time, considerable thicknesses of syn-orogenic sediments accumulated, the beginning of the orogeny coinciding with the change in sedimentation already mentioned.

Following the views of the 'Apennine Geology Research Centre', the orogeny may be considered to have resulted in the successive uplift of six or seven ridges. These ridges run roughly north-west–south-east, and several of them remain as topographical features. The oldest is that in the south-west, nearest to the Tyrrhenian Sea, and progressively younger

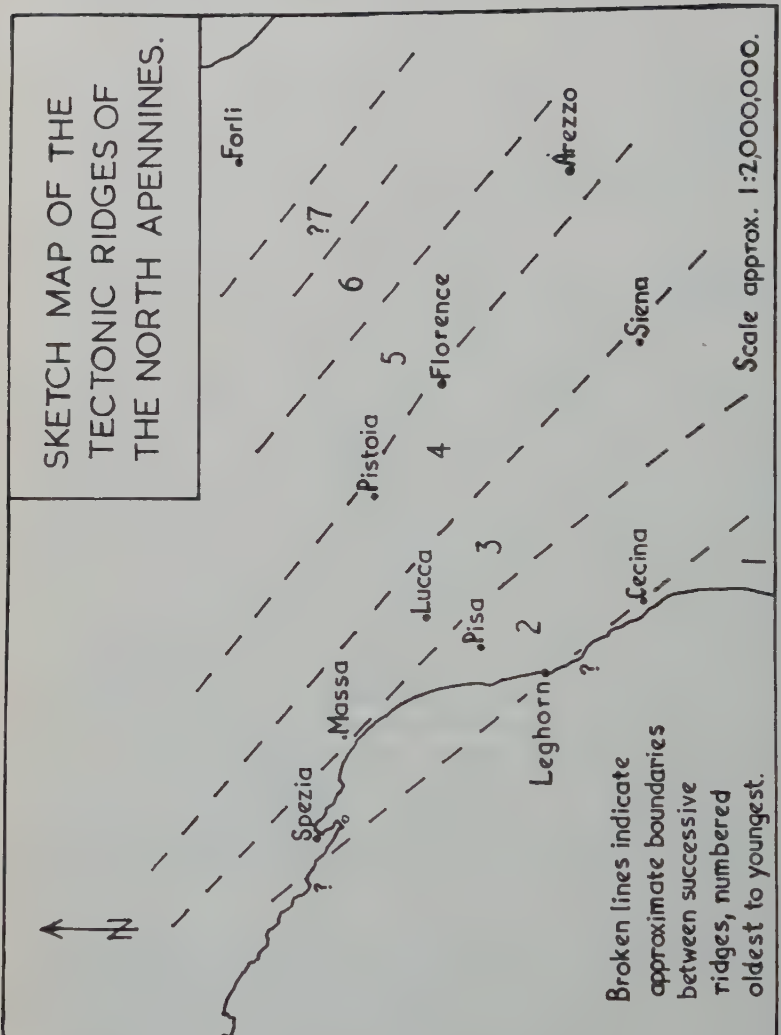

SKETCH MAP OF THE TECTONIC RIDGES OF THE NORTH APENNINES.
N
Forli
Arezzo
Florence
Siena
Pistoia
Lucca
Pisa
Massa
Spezia
Leghorn
Cecina
?7
6
5
4
3
2
1
?
?
Broken lines indicate approximate boundaries between successive ridges, numbered oldest to youngest.
Scale approx. 1:2,000,000.

Fig. 1. Sketch-map of the North Apennines showing the postulated positions of the six or seven tectonic ridges, after Merla, 1952 (simplified)

ridges appear to the north-east (see Fig. 1). There may have been even earlier tectonic ridges which were submerged in Quaternary times together with the land-mass that supplied the sediments.

Each ridge is thought to correspond to a system of faults converging downwards on a point within the zone of plastic deformation. Fig. 2 represents an idealised ridge of this type, though it is not to be supposed that they were all identical in structure. The faulting is considered to have been brought about by compressive forces operating along north-east–south-west lines. Generally the faults are steeper on the south-west side of each ridge. Migliorini described these structures as 'composite wedges'. They are best developed in the calcareous Apennines, south of the area under consideration. In the northern Apennines, the relatively plastic *Macigno* forms the usual top of the autochthon.

All the sediments which have been considered so far, belong to the autochthonous or unmoved series. With the orogeny, however, there came into the region of the present Italian mainland a series of allochthonous sediments which had travelled, by tectonic agencies, far from their original place of deposition. This allochthonous series, or allochthon, is widely distributed in the northern Apennines, and was interpreted formerly either as an unconformable cover of Tertiary rocks, or as a great nappe (the 'Ligurid nappe') coming from the south-west. The modern school of Migliorini and Merla has abandoned both these hypotheses and instead postulates a series of great submarine orogenic landslips, starting in the south-west and carried forward by the rise of successive tectonic ridges (see Migliorini, 1952).

In the main the allochthon consists of the *Argille scagliose* or 'scaly clays'—a highly disturbed shaly formation, formed of shattered argillaceous rocks and containing exotics up to the size of mountains. The exotics yield fossils which range in age from Jurassic to Oligocene. Many of the rocks of the allochthon are not known *in situ* (i.e. in the autochthon) on the Italian mainland. They must therefore have come from an outside source, and it is assumed that they came from unknown outcrops in the area of the Tyrrhenian Sea. There is plenty of confirmatory evidence favouring this hypothesis. Thus, notable among the exotics of the allochthon are masses of 'ophiolite' or 'greenstone' (serpentine, gabbro, pillow lavas, etc.), which are associated with a limestone that yields the Lower Cretaceous tintinnid *Calpionella*. No greenstones are known in the Mesozoic succession of the autochthon. At the same time it is noteworthy that these Jurassic exotics are large and abundant near the coast to the south-west, but decrease in size and abundance towards the north-east.

As each tectonic ridge rose in turn, the incompetent cover of *Argille scagliose* soon began to move under the force of gravity. Migliorini has estimated that only slight elevation was necessary for such landslipping to

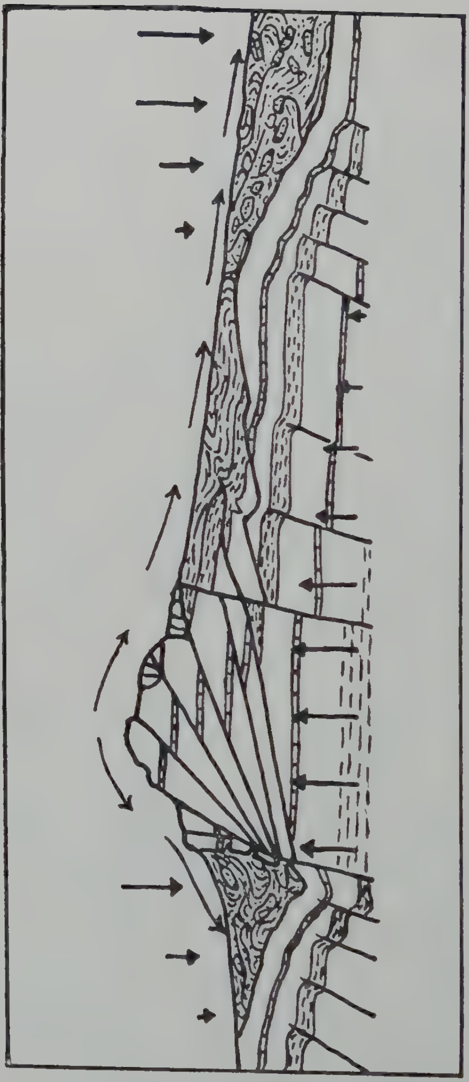


Fig. 2. Idealised section through a composite wedge; thin arrows indicating direction of land-sliding, thick arrows indicating later isostatic displacement (after Migliorini, 1952)

begin. The slips were likely to be in both directions, but in each case those moving inwards (i.e. towards the south-west) were soon stopped by the preceding ridge. Thus the main movement was always towards the north-east. As the allochthon moved onwards, later and later sediments were involved and over-ridden, until the intensity of the phenomena slowly declined and eventually ceased in Quaternary times. Isostatic readjustment also played an important part in the process by raising the ridges as topographical features and thereby instigating the huge landslips.

One important corollary of the successive landslip theory is that considerable lateral displacement of the allochthonous cover may occur without appreciable crustal shortening. This is especially important if, as suggested by Migliorini (1952), the principles deduced from the Apennines are found to be of more general application. He has suggested, for example, that the Cornish killas may have been comparable in its mode of origin to the *Argille scagliose*.

As the intensity of the earth-movements declined, then the syn-orogenic sediments being deposited on the allochthon were moved progressively shorter distances. Thus it is supposed that the *Loiano* formation was laid down near a coastline to the south-west of the deep sea in which the *Macigno* was accumulating. As a result of the movements, the former was carried over the latter to a distance of about 120 kilometres. However, later Miocene deposits appear to have moved only about fifty kilometres and certain Pliocene beds about five kilometres. At one place in the North Apennines, the *Argille scagliose* is known to rest on a Villafranchian (lower Pleistocene) deposit, and this is the latest datable movement.

During Pliocene and Pleistocene times various lake deposits accumulated between the ridges; for example, near Florence. Most of the higher ridges show evidence of glacial action, though only the last glaciation appears to be represented. The penultimate glaciation, if present at all, was of a lesser extent. An uplift in late Pleistocene times is inferred, therefore.

## 3. DAILY ITINERARIES

### Friday, 17 September

As the main party had arrived the previous evening, Friday morning was spent in examining the architectural and artistic beauties of Florence.

In the afternoon, an excursion was made by coach to the town of Fiesole (about five kilometres north-east of the city). This was intended as an introduction to the main stratigraphical elements to be seen in the North Apennines. Fiesole stands on what is interpreted as part of the fifth ridge, with a very steep southern limb and a less steep northern limb. Ascending the road beyond the village, a fine view was obtained of the countryside to the north, most of the hills being formed by the allochthonous *Argille scagliose* resting on autochthonous *Macigno* sandstone. Hereabouts the former includes great masses of exotic Eocene limestone (*Alberesi*).

Near here exposures were seen of typical *Argille scagliose* which took the form of an extremely broken-up shaly deposit, with no recognisable bedding, containing exotic blocks of marl and marly limestone up to 15 ft. in length. Continuing up a track through the woods, an exposure was seen of what appeared to be almost undisturbed rock resting on the highly disturbed *Argille scagliose*. In fact this was an exotic mass of Upper Cretaceous calcareous sandstone (*Pietraforte*), caught up in the allochthon and not known in an autochthonous condition anywhere on the Italian mainland. It has yielded *Inoceramus*, and Senonian ammonites have been found elsewhere in this area. Farther on, exposures of *Argille scagliose* were seen overlying the *Pietraforte* and proving its exotic character.

A slight descent was made to view a series of large quarries in the underlying autochthonous Macigno Sandstone. This consists of a series of graded beds of sandstone interbedded with shaly layers. Dr. Azzaroli mentioned that graded beds had been observed up to as much as 20 metres in thickness; the total thickness of *Macigno* here appeared to be about 400 metres. In the quarry known as Cava di Maiano, the party observed several of the sedimentation features described by Kuenen & Migliorini (1950); notably 'convolute bedding' (see Plate 8 A) and flow markings. Here the sandstone units appeared to be graded in their upper and lower parts, but to be fairly uniform in grain-size throughout the greater part of their thickness. Further quarries showed layers of indeterminate plant remains in the sandstone, and lignitic seams. Large slumps were also seen, all directed towards the north or north-east. These directions are characteristic of the *Macigno* and agree with the concept that the sediment came from the area of the Tyrrhenian Sea.

The party now reached the south side of the hill below Fiesole and obtained an excellent view of the fourth ridge beyond Florence. The city stands in a Quaternary basin between the two ridges and near to a Villafranchian lake deposit (see Fig. 5). In the evening Dr. Azzaroli kindly showed the party round the Geology Department of the University, where members were especially impressed by the large and excellent collection of Quaternary mammals in the lower of the two museums.

## Saturday, 18 September

The chief objective of the excursion on the second day was to examine the older rocks of the autochthon between Florence and Pisa.

The party left Florence by coach and proceeded west-north-west along the main road, across Quaternary deposits, to Pistoia. From here, the route lay westwards into the region of the fourth ridge, where the autochthonous Mesozoic inlier of Monsummano was examined. This has been described by Dr. Azzaroli (1949). The coach was left on the plain, just beyond the new town of Monsummano; the old town was built on a hill-top (as is usual in Tuscany). The party then climbed to a large quarry in the core of the inlier (see Fig. 3). The main part of this quarry was in massive grey limestone of the Lower Lias, with a great slickensided fault-plane forming the actual face of the quarry and separating the massive limestone from the bedded limestones and cherts of the Middle and Upper Lias. Characteristically these limestones are very unfossiliferous, though a few ammonites have been found in them. Here the bedded limestones (with *Posidonomya*), of Middle Jurassic age, are faulted out. After climbing up the east side of the main quarry to a higher quarry, the massive Lower Lias limestone was seen again beyond the main fault of the inlier, which fault has a throw of about 200 metres. Dr. Azzaroli demonstrated the anticlinal structure of the hill, the fold striking west-north-west–east-south-east and being slightly overturned to the north-east. Following a track round the hill, exposures were seen of dark red radiolarian cherts (*Diaspri*) of Upper Jurassic age. These were followed by the *Scaglia* or *Schisti policromi* of Cretaceous to Oligocene age, which presents a marly limestone facies here. The *Schisti policromi* is faulted against the *Argille scagliose* of the allochthon.

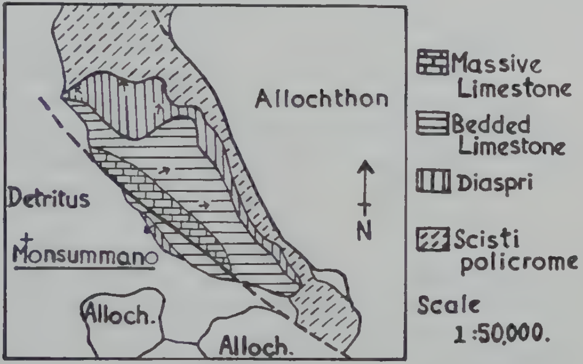


Fig. 3. Sketch-map of the Mesozoic inlier near Monsummano (after Azzaroli, 1949)

Then the party returned to the coach and proceeded through the new town of Montecatini, across a second Mesozoic inlier, to Marliana. Here an old quarry was visited on the north-east side of the hill on which the village stands. This showed the upper part of the *Scaglia*, with thin bands of limestone. The topmost beds of limestone were brecciated and contained the broken tests of large Oligocene foramifera such as *Lepidocyclina*. These deposits, though not very well developed at this locality, are the famous *Brecciole nummulitiche*. They are thought to mark the beginning of a period of coarse terrigenous deposition, and were laid down by turbidity currents. They contrast with the gentle deep-water deposition of earlier times.

The coach then carried the party on across another wide area of Quaternary continental sediments to the Palaeozoic hills south of Lucca, situated in the third tectonic ridge (see Fig. 5). In the region of Monte Pisano the party examined a long ditch section in the Valley of Guappero. This showed part of the Palaeozoic core of the third ridge. Such a core is not visible in the younger ridges to the north-east. The slight metamorphism of the Palaeozoic rocks at this locality probably originated during the Hercynian earth-movements. The section examined was mainly in reddish phyllites which have yielded Permian plants such as species of *Sphenophyllum*. A Carboniferous flora is known in similar phyllites elsewhere. Higher in the section, loose boulders of a quartz conglomerate were seen. These had come from outcrops of the *Verrucano*—a coarsely clastic and highly distinctive deposit which marks the top of the Palaeozoic rocks (see above, p. 330).

Returning to the main road, the coach carried the party up through Monte Pisano and down across the Quaternary coastal plain to Pisa. The famous bell-tower in Pisa was seen from a considerable distance. Also, Dr. Azzaroli pointed out Monte Verruca, to the south, as being the type locality for the *Verrucano*.

### Sunday, 19 September

The party had now examined representative sections in the third, fourth and fifth ridges respectively. The first and second ridges, which were to be examined from a headquarters at Pisa, are only represented at intervals, as a result of Miocene or Pliocene (or possibly post-Pliocene) foundering. A considerable part of this region is covered by deposits of very late geological age.

The object of the excursion on the third day was to examine the remnants of the first tectonic ridge, south of Pisa. Leaving the latter in a south-westerly direction, the party reached the coast at Livorno (Leghorn) and followed it southwards. About eight kilometres south of Leghorn there occurs a small outcrop of supposed *Macigno* which was examined in reefs on the beach. Neither the relationships nor the thickness of this deposit can be determined because it is surrounded on all sides (landward) by allochthonous *Argille scagliose*. It was seen to be less well-bedded and much coarser in grain than it is in the exposures at Fiesole. Nevertheless, its age equivalence at the two localities has been shown by the presence of rare molluscs, such as species of *Meretrix* and *Panopea*. The coarser grain and presumed thicker development of the *Macigno* on the Tyrrhenian shore is taken as evidence for the derivation of the sediment from that direction. False-bedding, however, appears to imply derivation from the north-west, though certain members of the party expressed doubts as to the validity of this criterion.

After continuing southwards along the coast to Castiglioncello, a stop was made to examine an exposure of 'greenstone' in the allochthon. These 'greenstones', which are probably of Jurassic age, are both extrusive and intrusive in origin. Apparently some were submarine, being commonly associated with radiolarian cherts. They occur in scattered blocks throughout the allochthon but are larger and less broken-up towards the Tyrrhenian coast. As there are no traces of vents, or other volcanic phenomena, in the Jurassic rocks of the autochthon, these 'greenstones' are thought to have been emplaced west of the present coastline.

The 'greenstone' examined at Castiglioncello appeared to be entirely composed of serpentine. This aroused some discussion as to the possible existence of serpentine lavas. The route continued to San Vicenzo where lunch (and bathes) were taken within view of the island of Elba. This famous island may represent part of the lost Tyrrhenian land-mass. Special interest attaches to the Quaternary deposits of the small island of Pianosa, a few miles south-west of Elba, which contain fossil mammals—many of them dwarfed. Some genera, such as *Bos* and *Cervus*, must have migrated there from the mainland later than Villafranchian times, thus implying subsidence of the land connection very late in geological time.

After leaving the main coast road, the route lay inland towards the Monti di Campiglia which represent the first of the tectonic ridges. Hills of Tertiary acid volcanic rocks were seen to the north. Associated intrusive rocks have produced considerable metamorphism and mineralisation in the Mesozoic core of this ridge. On entering the *Botro ai marmi* ('Valley of Marble'), to the left of the road a quarry was visited which shows the bedded limestones of the Lias and Middle Jurassic recrystallised into a fine white marble. Above the quarry the party examined the tip-heaps (mainly slag) of an old antimony and lead-zinc mine. In the brief time available, these yielded specimens of lead-zinc ore and associated skarn minerals, especially ilvaite. A short distance farther up the valley, in a stream below a working quarry in the limestone, the party saw a very small exposure of fine-grained acid granite. This rock is thought to be extensive underground, though only exposed in this small area, and its implacement is held to have been responsible for the metamorphism of the limestone.

Farther on, a track was followed through the woods to examine a porphyritic acid dyke in the limestone, though the party appeared to be more interested in the abundance of wild figs in the vicinity. The coach then returned to Pisa in the dark, via Campiglia Marittima and the coast road—a hair-raising experience due to both the precipitous road and to the driving.

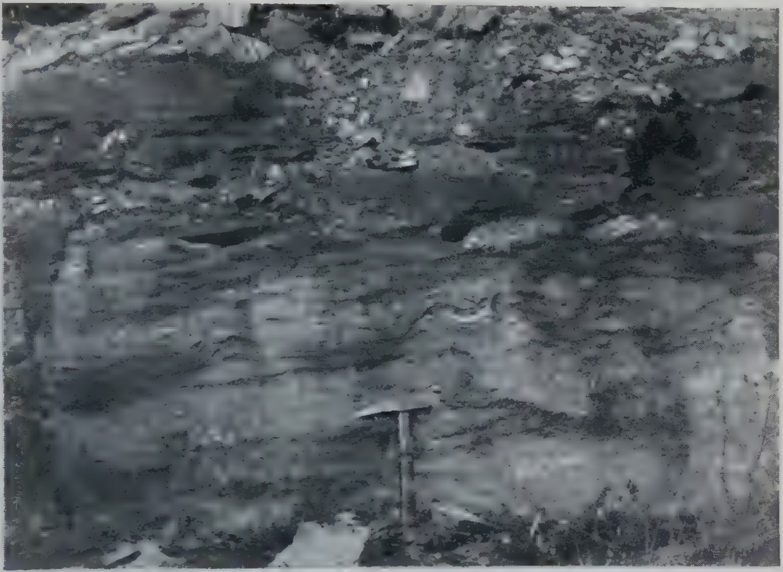
### Monday, 20 September

The main object of the excursion on this day was the examination of the steam-vents and other volcanic phenomena around Lardarello, south-east of Pisa. The route lay eastwards along the valley of the Arno and then south along its tributary, the Era (see Fig. 5). At first the strata traversed were Pliocene sands, which support a rich vegetation, but after Capannori the underlying Pliocene marine clays give rise to a barren countryside. Beyond Saline, masses of gypsum were seen at the roadside, indicating the brackish-water clays of the Upper Miocene. Besides gypsiferous horizons, this formation includes rock-salt, lignites and conglomerates. There appears to be only one fossiliferous horizon, which yields opercula of the brackish-water gastropod *Bithinia.* Fossiliferous marine Miocene deposits are known only on the Adriatic side of north Italy, and farther south, in the province of Grosseto.

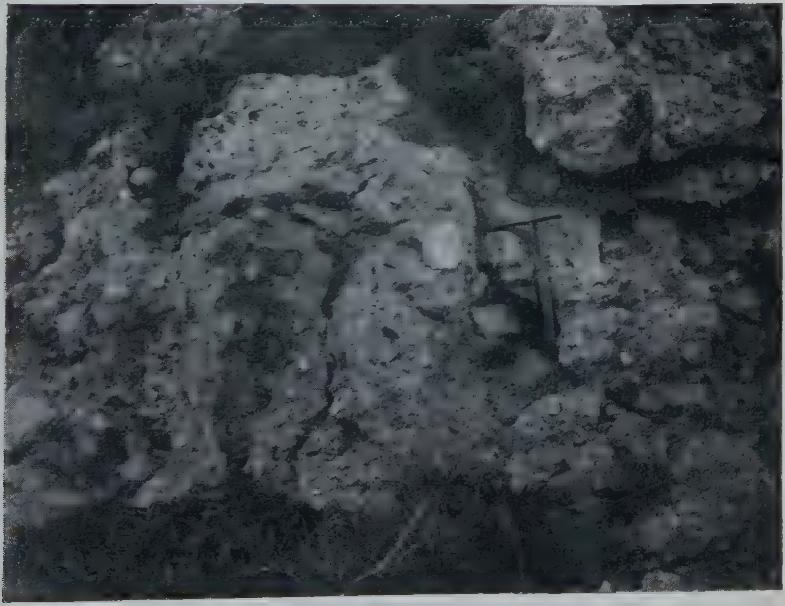
At Pomerance, a ridge was crossed which is formed by Pliocene capped by tufaceous limestone. As the coach approached Lardarello, the allochthonous *Argille scagliose*, including great masses of serpentine, was seen again. The route then entered the well-known region of the steam-vents of Tuscany, which provide much of the natural power of north Italy. This region lies between the valleys of Cecina and Cornia and comprises more than eighty square miles, though in only a part of this area is the activity on a scale large enough to be used for the generation of electricity. The steam appears at the surface in the form of white and shifting fumaroles (*soffioni*), which can be seen scattered about the countryside. In some places the steam emerges through basins of muddy water (*lagoni*).

Possibly the steam-vents were referred to by Lucretius as long ago as the first century A.D. Certainly they have been well known since the thirteenth century. Boric acid was discovered here in 1777 and from then onwards commercial development proceeded rapidly—mainly under the direction of the Comte de Lardarel (a refugee from the French revolution) who gave his name to the principal centre of industrialisation. Nowadays, instead of utilising natural vents, the steam is obtained from borings and conveyed directly to power stations for the generation of electricity.

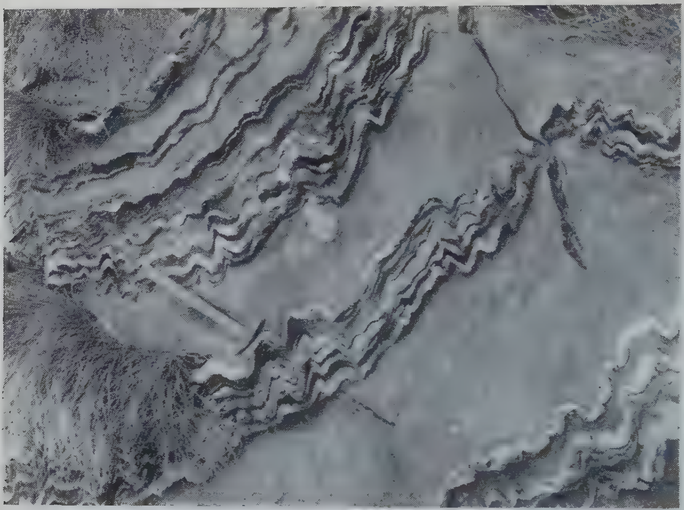
Geologically, the region consists of *Argille scagliose* resting on autochthonous Trias (including Rhaetic). Autochthonous Jurassic, Cretaceous and Tertiary rocks have not been found in borings around Lardarello, though they are known near by. The argillaceous nature of the allochthon makes it a good cover for the underground steam, which is obtained from borings under great pressure (up to 380 lb./sq. in.) and at a high tempera-



A. Convolute bedding in a shaly horizon of the Macigno Sandstone; Cava di Maiano, Fiesole, near Florence. (Photo. J.H.T.)

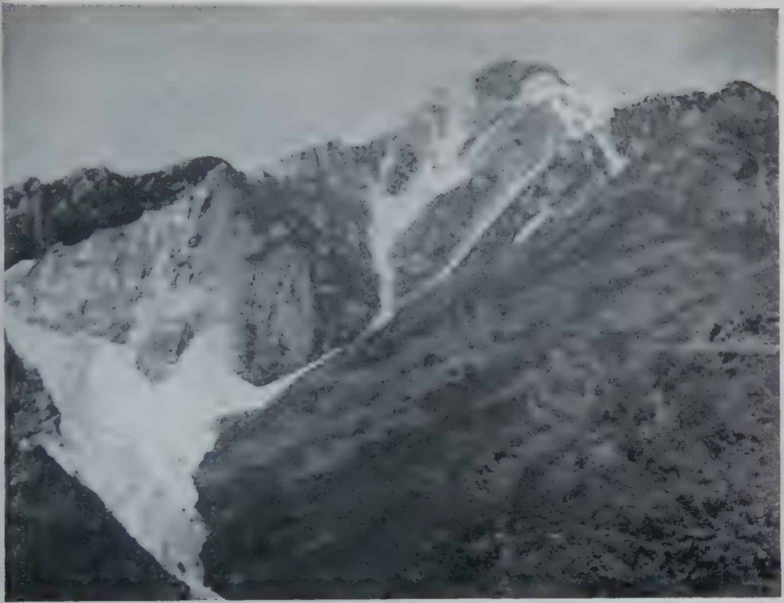


B. Tectonic slide-plane breccia with marble pebbles, separating *Calcare cavernoso* above from Carrara marble below; near Campocecina, Alpi Aquane. (Photo. J.H.T.)

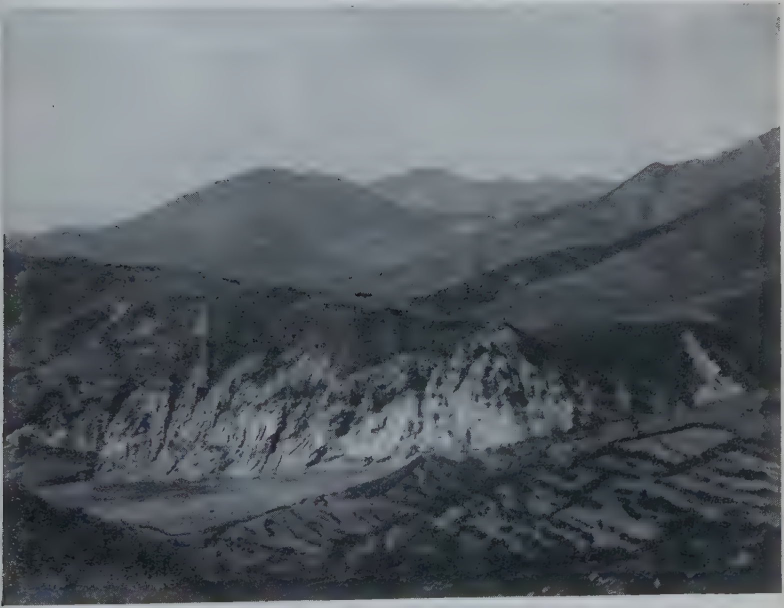


A. *Cipollini*, contorted and metamorphosed Jurassic limestone with chert bands; near Campocecina, Alpi Aquane. (Photo. F.H.B.)

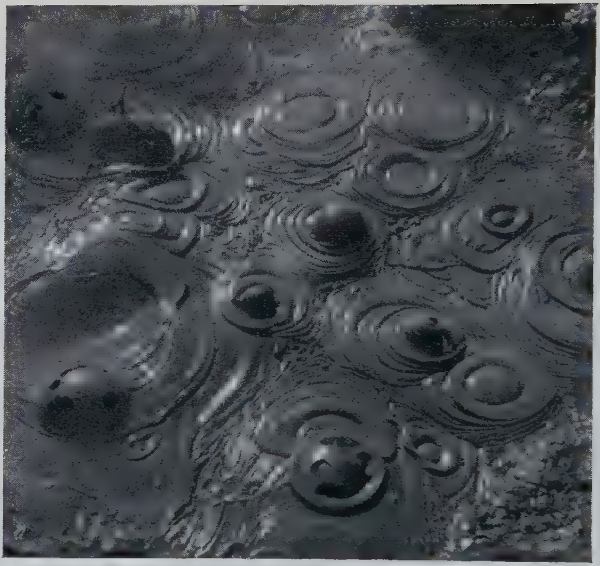
B. Fracture cleavage in Liassic limestones and shales; near Campocecina, Alpi Aquane. (Photo. F.H.B.)



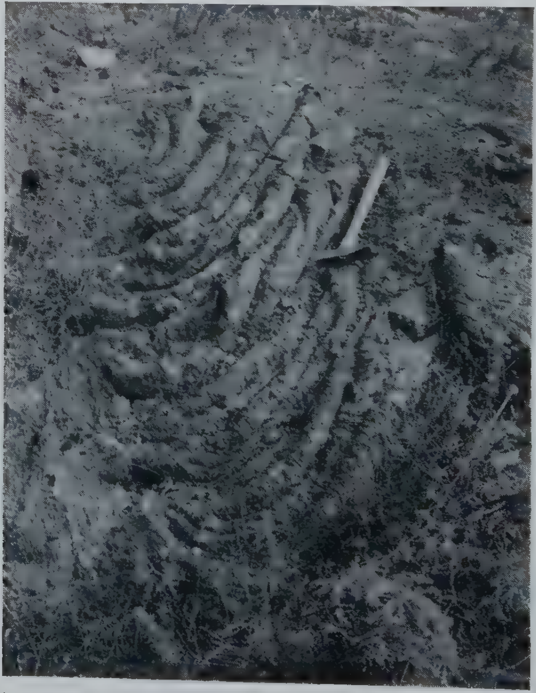
A. Syncline in the over-ridden series, overturned towards the right of the picture and showing core of white Carrara marble: Monte Altissimo, Alpi Aquane. (Photo. J.H.T.)



B. Strongly contorted alternations of Triassic dolomite and gypsum, seen across valley formed by transverse fault in the fourth tectonic ridge; above the village of Sassalbo, near Collagna. (Photo. J.H.T.)



A. Natural gases bubbling through a muddy pool in the crater of Solfatara, near Naples. (Photo. A.V.J.)



B. Ropy lava on the western flank of Mount Vesuvius, near Naples. (Photo. F.H.B.)

ture (up to 419°F.). The steam is tapped chiefly along fault-planes trending north-west–south-east. Recently geophysical prospecting has helped considerably in the tracing of these faults, but great accuracy is necessary in order to enable the latter to be met by narrow borings.

The origin of the steam, and its accompanying gases, is a matter of some dispute. In their high temperature and high pressure the vents are comparable with the geysers of Iceland and New Zealand; in their general characters perhaps they are more like the *solfatara* seen later by the party near Naples. Local geologists have postulated a magma chamber supplying the steam from a depth of two to two and a half miles. A deep-seated origin is suggested by the relatively high radio-activity of the steam. These and other matters relating to the steam-vents of Tuscany have been discussed in English by A. Mazzoni (1948).

At Lardarello, officers of the Societá Lardarello took the party to see a typical boring in operation. Along the same fault system several other borings were passed, where steam was already being obtained, either from the Trias or from the junction between the Trias and the Palaeozoic basement. Dr. Azzaroli pointed out that, until recently, the cover of *Argille scagliose* was thought to be an unconformable series of Eocene rocks.

When the party had returned to the works, one of the safety valves on a steam pipe was opened, to show the tremendous pressure of the steam. Then the party was conducted round one of the power stations. There are two main installations at Lardarello and two smaller ones in villages farther south.

Afterwards the party had the pleasure of taking wine with the management, and Dr. A. F. Hallimond (who represented the President during the visit) expressed the Association's thanks to the Societá Lardarello for a most interesting demonstration.

The route then lay southwards from Lardarello across a Mesozoic inlier in the core of the second tectonic ridge, near Castelnuovo di Val di Cecina. After lunch on a ridge of *Macigno*, the party went on to Monte Rotondo. Here natural steam is trapped for the extraction of boron. The party followed a path up the hill above the village, and passed exposures of *Scaglia* from which hot air was escaping through small openings. Higher up the hill, natural emissions of sulphurous steam were seen to be rising from fractures in an outcrop of Jurassic limestones and cherts. The party observed perfect, but extremely fragile, crystals of sulphur, and the chert was seen to have been whitened by the action of the steam. Here the steam comes from Mesozoic rocks which are absent at Lardarello.

Then the party returned towards Pisa by the same route. A halt was made near Montecerboli to examine poor exposures of Miocene clays with gypsum, faulted against serpentine of the allochthon. Farther on there was a diversion to Montecatini di Val di Cecina, a village at the top of a hill mainly composed of allochthon but surmounted by unmoved late Tertiary deposits. Here was seen one of the very rare Tertiary igneous rocks of the second ridge. This was a minette, in contact with Pliocene sediments. It was exposed in a much weathered condition beside the track which leads down hill from the centre of the village. Fresher material was found loose near by. The party then returned to Pisa.

### Tuesday, 21 September

At the Director's suggestion no official geology was done on this day, but instead the party took the opportunity of examining Pisa cathedral, with its famous leaning bell-tower, and of bathing at Leghorn or the seaside resort of Viareggio.

### Wednesday, 22 September

This day was devoted to an examination of the Mesozoic rocks of the Alpi Aquane, north of Pisa (see Fig. 5). The party left Pisa early and took the coast-road northwards past Viareggio, and then inland, via Massa, towards Carrara. Here the route entered the wonderful mountain scenery of the Alpi Aquane, which form part of the third tectonic ridge. At first the hills were mainly composed of Triassic *Calcare cavernoso*, very much faulted hereabouts. Then a halt was made near Castelpoggio to examine cuttings in dark Rhaetic argillaceous limestone which have yielded *Pteria contorta* and other characteristic fossils.

The Alpi Aquane are complex tectonically, part of the normally autochthonous and unmetamorphosed Mesozoic sequence having been thrust over metamorphosed rocks of the same age at this point. The most notable of the metamorphosed Mesozoic rocks of the area is the Carrara marble, which is world-famous on account of its use in statuary and in building. This is a massive Liassic limestone that has been metamorphosed by the weight of over-riding sediments.

On the road to Campocecina, bedded unmetamorphosed strata were seen to rest on the white marble. It is thought that the former have been carried from the second ridge, and the plane of movement was shown to be dipping to the south-west. From this locality, the second ridge was clearly visible, beyond the bay of Spezia, and behind this again, the supposed first ridge could just be distinguished (see Fig. 1).

Further exposures beside the road showed the Triassic *Calcare cavernoso* resting on the marble. The former, which is interpreted as a collapse-breccia, was separated from the marble by a purely tectonic slide-plane breccia (see Plate 8 B). A little farther on, at the top of a ridge, exposures of the distinctive *Cipollini* (see Plate 2) were seen, which is the metamorphic equivalent of the bedded limestones and cherts of the later Lias and Middle

Jurassic. At this point the limestone takes the form of a black marble while the chert bands are very strongly contorted.

Then the party climbed the mountain of Campocecina, passing a number of excellent sections in the highly-disturbed beds of the over-riding series. These consisted mainly of *Scaglia* and *Calcare cavernoso*, but also included strongly cleaved Liassic limestones and shales (see Plate 9 B). From near the top of the mountain, quarries could be seen below, in the white marble of the over-ridden beds. Unfortunately a thick haze obscured the view that would have been visible from here, but some compensation for this resulted from the unexpected discovery of a cottage, near the summit, where *Chianti* was sold.

After descending to the coach, the party was taken to Carrara, the centre of the marble industry. Here, through the agency of the coach-driver, the party visited some of the workshops where local craftsmen were producing statues which were to be sent all over the world. Then the party went on to the town of Pietrasanta where they were accommodated for the night.

### Thursday, 23 September

This day was spent in traversing the third tectonic ridge, with its well-displayed structures, and in reaching the core of the fourth ridge. At first the route lay northwards from Pietrasanta, into the Palaeozoic core of the third ridge. At Corvaia, metamorphosed *Verrucano*, in the form of mica-schists with quartzite pebbles, was seen behind a row of houses. Then the coach climbed into mountains composed almost entirely of metamorphosed Upper Palaeozoic rocks. Near the top of the watershed, a large overturned synclinal structure was seen in Monte Altissimo (see Plate 3). In this structure, Triassic dolomites succeed the Palaeozoic rocks and enclose a core of Jurassic marble. The extensively-quarried white marble gives the mountain a snow-capped appearance.

The top of the ridge was penetrated by a narrow tunnel (the *Gallerie Cipollaio*), still in the process of being widened. Here the party had the remarkable experience of being involved in a 'traffic-jam' in the heart of the mountain. When the other end of the tunnel was reached, an entirely Mesozoic countryside was discovered. Just beyond the mouth of the tunnel, were strongly-sheared, dark marbles, transitional between the Triassic dolomites and the white marbles of the Lias.

Whilst descending the deep valley beyond, a series of fine glacial corries and V-shaped valleys were seen on the left. The succession through the Carrara marble, the *Cipollini* and the *Scaglia* was ascended slowly, the Upper Jurassic being missing, here, as a result of a tectonic break. Eventually the *Macigno* was seen in road-cuttings at Isola Santa. In this neighbourhood it was metamorphosed by the weight of the over-riding allochthon, but in places where it was not too disturbed shale bands and graded bedding were still visible.

In proceeding north-eastwards across the remainder of the third ridge, the succession was crossed twice more. Dr. Azzaroli pointed out that dragfolds in the overlying series suggested movement from the north-east, and not from the south-west as might be expected. As yet no explanation has been offered for this anomaly.

The low-lying ground between the third and fourth ridges was reached near Castelnuovo di Garfagnana. In this area Pliocene continental deposits rest unconformably on both the autochthonous and the allochthonous series. Near Castiglione di Garfagnana a wayside exposure was examined in an Upper Pliocene fresh-water conglomerate. The party noted occasional pebbles of white marble. Farther on, near the Villa Collemandina, a stream exposure was seen in Lower Pliocene silty clays with lignite. Some of the pieces of lignite reached the size of tree-trunks. Many fossils have been found in the Lower Pliocene of this area, including *Mastodon*, *Tapir*, *Magnolia* and *Liquidambar*.

The party now returned to the fourth ridge, and examined the Mesozoic inlier of Pania di Corfino. Lower Lias limestone is well exposed beside the bridge below the village of Corfino, faulted against the *Scaglia* and *Macigno* which underlie the valley. This fault has a throw of about 400 metres and trends north-north-east–south-south-west. A second fault beyond, throws the Trias against the Jurassic. Near Corfino there is one of the few localities in the North Apennines where Mesozoic fossils are readily obtainable. At the beginning of the century Levi described a large fauna of ammonites and brachiopods from here. The night was spent at the delightful mountain-top village of Corfino, and the party passed much of the evening admiring the Alpi Aquane lit by the setting sun. After dark, Dr. Azzaroli conducted an informal discussion on the geology of the northern Apennines.

### Friday, 24 September

A traverse across the fourth tectonic ridge occupied most of the following day. The party left Corfino with regret and descended the mountain again, to retrace the route of the previous afternoon as far as Castiglione. There the coach turned northwards to Piazza al Serchio where, near the bridge, exotic blocks of pillow-lava were seen to form pinnacles in the allochthon. The lava, which is probably Jurassic in age, was associated with serpentine (although apparently not with the customary chert).

Allochthonous rocks were then seen for a considerable distance along a road leading through mountainous country, via Fivizzano, to Vendaso. Just north of Vendaso, near the village of Sassalbo, Dr. Azzaroli indicated the strong fault feature where *Alberesi* (Eocene marly limestone) of the

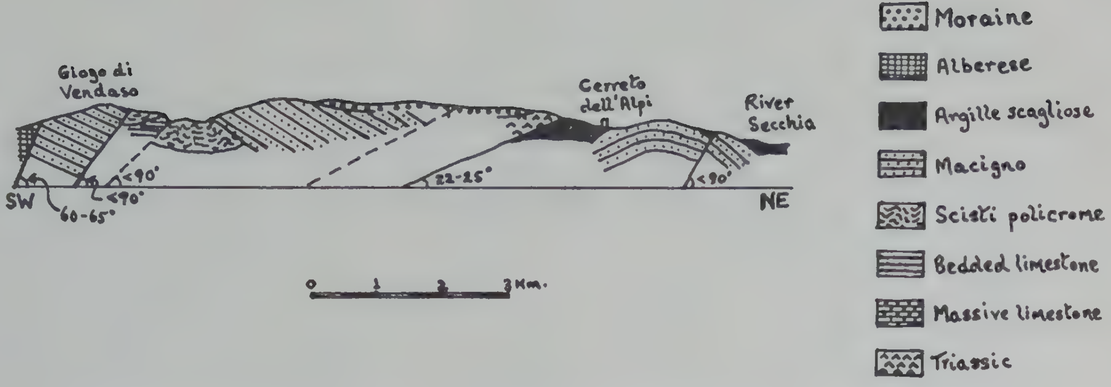


Fig. 4. Section across the fourth tectonic ridge between Fivizzano and Collagna (after Azzaroli, 1950, section VI)

allochthon is thrown against the *Macigno* on the south-west side of the autochthon of the fourth ridge. Then began a traverse across the ridge in an area which has been described by the Director (Azzaroli, 1951). The party followed almost exactly his sixth section (reproduced in Fig. 4), which may be taken as a typical section through an actual composite wedge. Dr. Azzaroli suggested that the fault demonstrated on the south-west side of the ridge probably represented the last phase of movement in Pleistocene times. This was supported by the 'youthful' appearance of the topography hereabouts.

The coach continued along the road above the village of Sassalbo, and across a repeated succession *Macigno; Scaglia;* Lias; *Scaglia; Macigno*. The Director considered the ridge had originated as a fold on which the *Argille scagliose* moved. The folding was followed by thrusting along the strike, though in some areas there was recumbent folding instead (see for example Azzaroli, *loc. cit.*, section III). Also there are many transverse faults, at right angles to the length of the ridge, and the party halted for some time to study the excellent section displayed on the opposite side of a transverse valley produced by such a fault (see Plate 10 B). This section showed a number of features, of which the most obvious was the sharply contorted Trias, consisting of alternations of black dolomite and white gypsum below, and *Calcare cavernoso* above. The Director thought that this might be the only place in the North Apennines where unaltered alternations of gypsum and dolomite could be seen at the surface. In the slopes behind could be seen the characteristic colours of the *Scaglia*, the Jurassic rocks being cut off tectonically in this area.

Farther up the valley, Dr. Azzaroli pointed out a patch of Palaeozoic mica-schists and amphibolite, surrounded by *Calcare cavernoso*. Then the party continued up the pass of Cerreto and took lunch opposite the fine glacial cirque of Monte La Nuda. A few members walked back a short distance down the hill to examine at close quarters a quarry in Triassic gypsum. Many other glacial features were seen in the vicinity, including extensive moraines full of boulders of *Macigno*.

The route continued down the far side of the ridge to La Gabellina, in a deep valley where the *Calcare cavernoso* was seen to be thrust over the *Argille scagliose* (see Fig. 4). Farther on, in the deep gorge of Schiocchi di Cerreto, the party examined a small anticline in which the *Macigno* displayed a much coarser facies than had been seen previously. Sections by the roadside showed a coarse-grained sandstone containing quite large pebbles, though still somewhat graded and with shaly partings. The pebbles were of granites, earlier grits and mud-pellets, among other rocks. Also there was a considerable amount of fossil wood. Lower down the gorge, general views were seen of an extensive countryside occupied entirely by allochthonous rocks, enclosing exotics of gypsum, *Calcare cavernoso*,

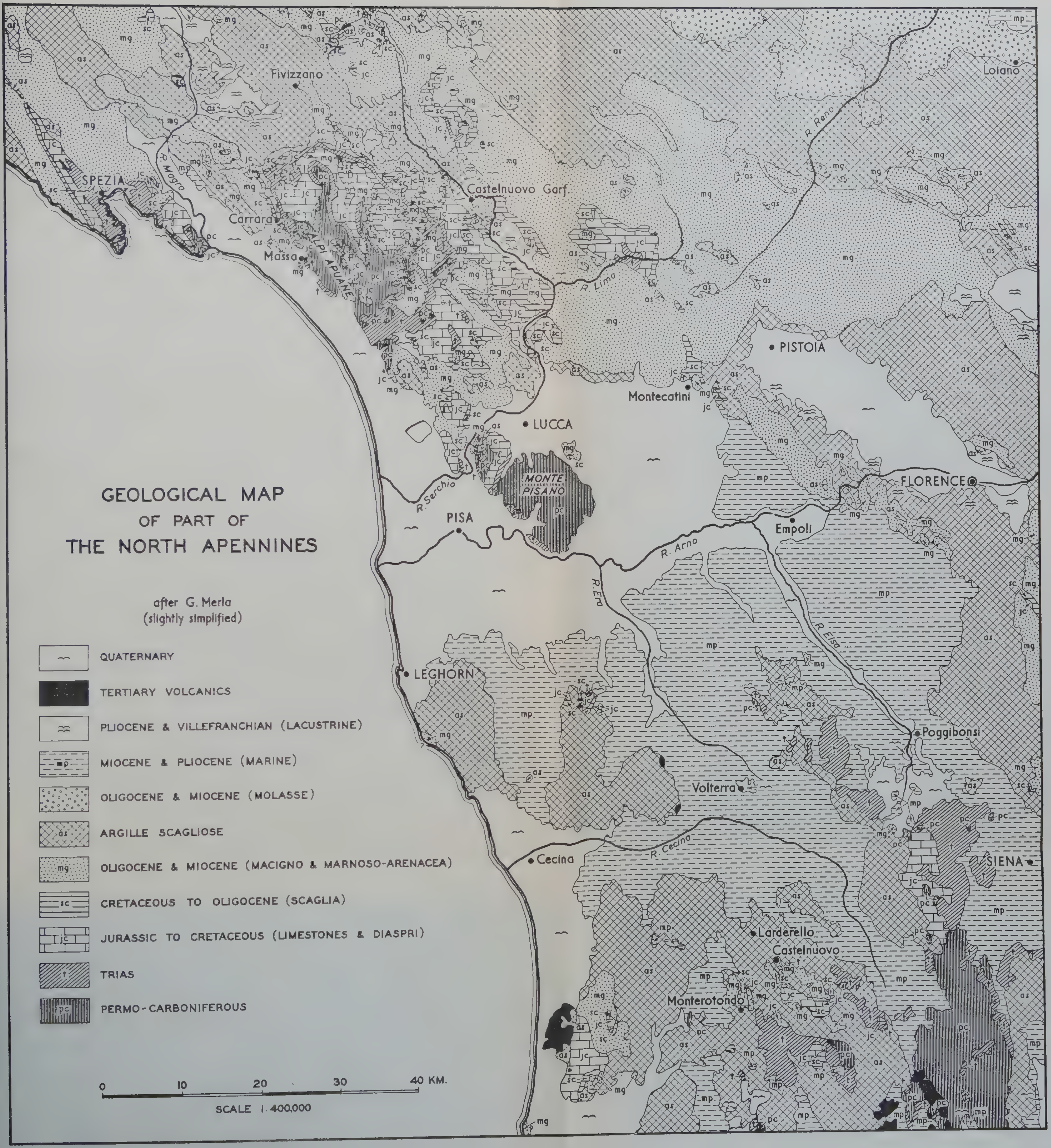


Fig. 5. Geological map of part of the North Apennines, after Merla, 1952 (simplified)

[*To face p.* 346

*Macigno* and *Alberesi* (the last-named especially in the upper part of the matrix of *Argille scagliose*). Here it was noted that the exotics were in a much more broken-up condition than were those on the south-west side of the ridge.

The day ended with a run through Collagna to Castelnuovo ne'Monti, the stopping-place for the night. After dinner that evening Alderman W. P. D. Stebbing (a former President of the Association) proposed a vote of thanks to Dr. Azzaroli for his inspiring leadership of the main part of the excursion, which was to finish the following day. This was heartily endorsed by all members of the party.

### Saturday, 25 September

The final day of the North Apennine part of the excursion was occupied by the return to Florence, mainly over Tertiary rocks. The party left Castelnuovo by the main road to the north-east, which crosses a plain that is dominated by the Pietra di Bismantova—a flat-topped mountain capped by marine Miocene limestone. Many small sections of marine Miocene clays, sandy limestones and sandstones were seen along the road to Vezzano. Then followed a long run, without halts, through the cities of Reggio Emilia, Modena and Bologna, and then south on the main road towards Florence. The final items in this part of the excursion were a few halts to study the molasse deposits of the Tertiary on the north-east side of the North Apennines.

Beside the main road, about ten kilometres north of Loiano, a series of small exposures were seen, showing a descending succession of unfossiliferous Pliocene sands and conglomerates resting uncomformably on Upper Miocene marine marls, rich in microfossils and resting, in turn, on Middle Miocene molasse. This lowest deposit attracted the greatest attention. It consists of well-bedded silty sandstones and is said to reach a thickness of about 120 metres. Certain members of the party were delighted to collect from this the only macro-fossils obtained during the excursion (apart from wood). Fossils found included sponges, echinoid spines and marine lamellibranchs.

Farther on, near the village of Anconella, lower deposits were examined. Poorly-exposed Lower Miocene calcareous marls were seen to rest on Oligocene molasse with slight unconformity. This was the Upper Oligocene, or 'Anconella' molasse, less than a hundred metres in thickness, and alternating in its lower part with the underlying clays. These latter are grey above and red below, and contain abundant micro-fossils. Below them is the Lower Oligocene, or 'Loiano' molasse, which is thought to be the far-travelled equivalent of the main part of the *Macigno*. Unconformities separate this from the later Oligocene deposits above, and the allochthon beneath. It is said to have been deposited on the *Argille scagliose* and then carried with it, from the south-west, to rest on top of autochthonous Miocene beds. The last are of an off-shore facies, and therefore considered to have been deposited to the north-east of the Miocene molasse.

Later, the conglomeratic lower part of the Loiano molasse was seen in a road-cutting near the type locality. It consisted of coarse sand with large boulders including those of quartz-porphyry and vein-quartz. Fragmentary specimens of *Nummulites* were also common here. Finally the coach crossed the Futa pass and descended to Florence.

### Sunday, 26 September

The party left Florence in the morning and travelled by train to Naples. On the way, about three hours were spent in Rome when most of the party were able to visit St. Peter's, the Forum and the Coliseum.

### Monday, 27 September

The morning was spent within the city of Naples. Some members visited the famous Marine Biological Station, whilst others examined the remarkable collection of articles from Pompeii, now preserved in the National Museum.

In the afternoon, the party went on a coach tour of the volcanic area of the Phlegraean Fields, west of Naples (see Fig. 6). This may be regarded as the centre of the great volcanic area which extended eastwards to Vesuvius and westwards to the island of Ischia. The whole area is floored by Cretaceous and Tertiary rocks. Subsidence began in the Pliocene period, and the huge trough so formed began to fill with volcanic lavas and pyroclastic rocks. The Phlegraean Fields include several low craters, but at the present day the only activity takes the form of emissions of sulphurous vapours and steam.

The coach followed the Via Antiniani westwards from Naples, passing near the famous Grotta del Cane, a cave in which carbon dioxide accumulates near the floor where it can suffocate dogs, but leave human beings unaffected. This is no longer considered an attraction for tourists.

The first stop was made at Solfatara, where the party entered the almost extinct, but highly commercialised crater. Here the chief item of interest was a large muddy pool in the wide, flat floor of the crater, through which natural gases were bubbling with considerable force (see Plate 4). Extensive deposits of sulphur, and other minerals, were seen in the walls of the crater, while on its north side two artificial caves could be entered to experience the Turkish Bath-like atmosphere produced by the rising steam, and to examine the fragile crystals of sulphur forming on the walls.

Then the coach took the party to Lake Avernus, a flooded crater which was thought by the ancients to be the entrance to the underworld. At this locality, roadside sections were examined in well-bedded volcanic ash

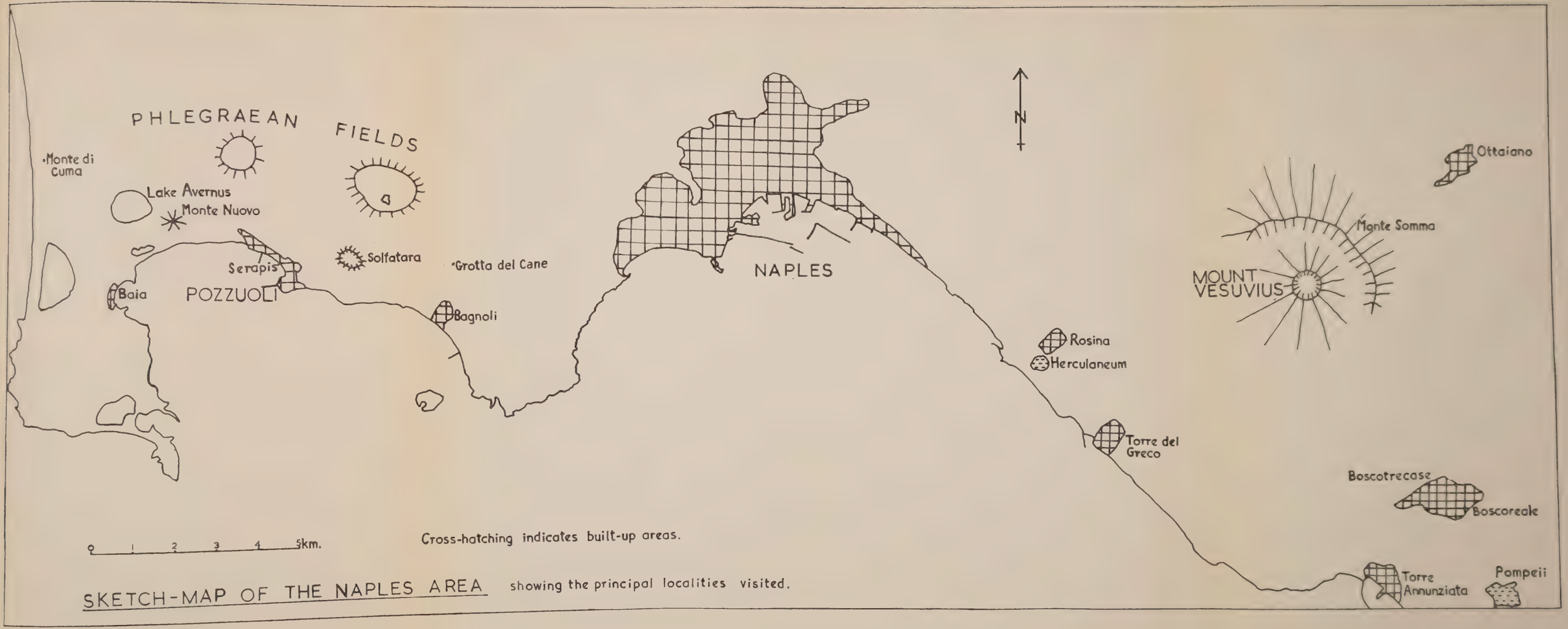


Fig. 6. Sketch-map of the Naples area, showing the principal localities visited

[To face p. 348

containing many bombs. Just east of Lake Avernus rises the perfect ash-cone of Monte Nuovo which appeared almost overnight in 1538, and which was described in detail by Sir William Hamilton in one of the first scientific works on volcanology.

The coach then proceeded westwards to the coast at Monte di Cuma, where the party examined the underground 'Grotto of the Sybil', an extensive structure excavated in the solid tufa of the hillside by early Greek settlers and only rediscovered in 1932. The return to Naples was made via the coast road. The last halt of the day was made just west of Pozzuoli, where the party examined the misnamed 'Temple' of Serapis, made famous to geologists by Charles Lyell in his *Principles of Geology*. The three pillars figured in Lyell's frontispiece, and on the obverse side of the Lyell medal of the Geological Society of London, clearly showed the borings made by marine molluscs when they were deeply submerged in sea-water. This was Lyell's outstanding proof of the rise and fall of sea-levels within historic time, and the party noted that the ancient market-place (not a temple) was in fact partly flooded at the time. Recently a geophysical station has been established near the pillars, where the relative motions between land and sea are now recorded accurately. Parascandola (1952) has suggested a correlation between the recorded movements at Serapis and the intensity of volcanic activity in the neighbourhood (see Fig. 7). The party then returned to Naples.

### Tuesday, 28 September

Early the following morning the party left by coach and proceeded south-eastwards along the *autostrada* to Pompeii, below the south-western slopes of Mount Vesuvius. *En route* they noted sections in various nineteenth-century lava flows which crossed the road, but traffic regulations did not permit stops to examine them. The morning was spent in exploring the wonders of the Roman city of Pompeii which was buried and preserved by the ash of the great eruption of 24 August A.D. 79. After lunch, the coach took the party back along the *autostrada* and up the winding road which climbs the western slope of Vesuvius. The coach had to be left at a height of about 600 metres, after which the party climbed another 150 metres by a narrow-gauge railway, and finally reached the summit via the chair-lift which replaced the famous funicular railway destroyed in the 1944 eruption.

The party was able to descend the inner wall of the crater for a short distance, to a small steam-vent, which, together with sulphurous odours, has constituted the only detectable activity of the volcano since 1944. By walking round the southern edge of the crater, members of the party were able to collect small bombs and perfect crystals of augite from the loose ash. Also they examined a lava flow of the last eruption. A few of the party

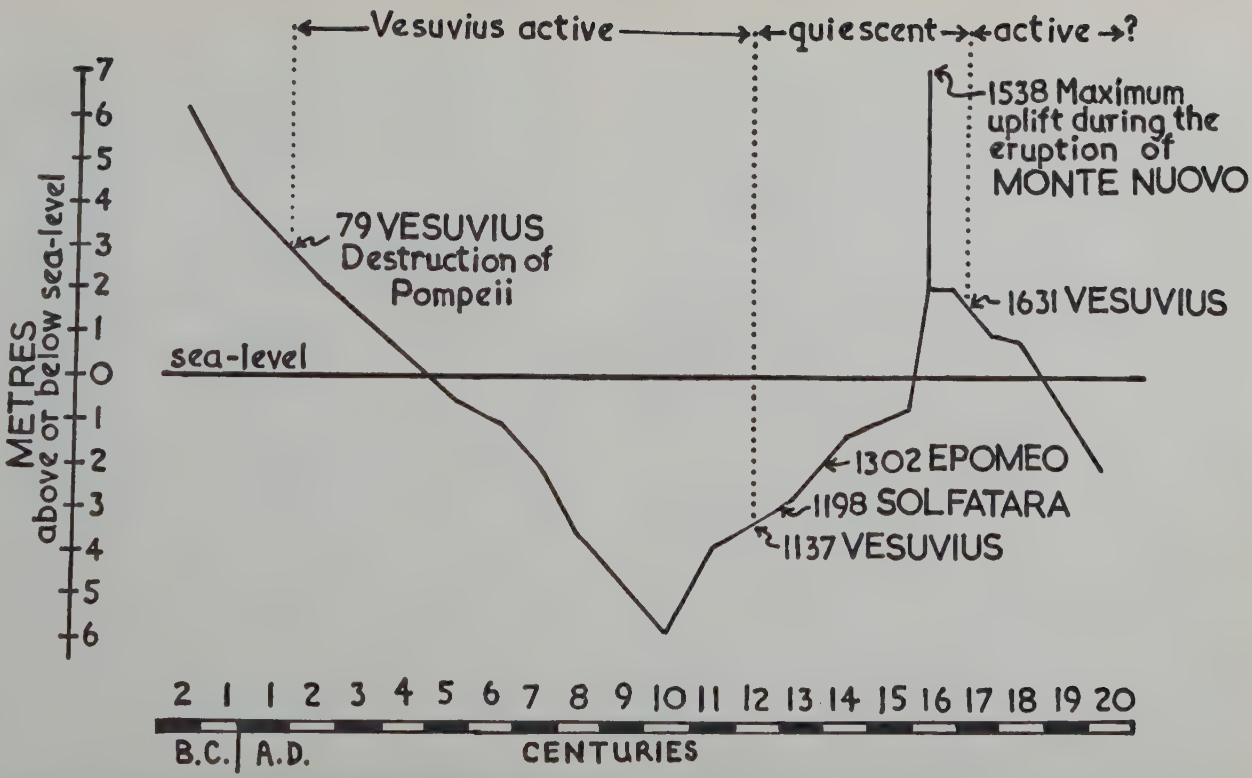


Fig. 7. Graph showing the rise and fall of the 'Temple' of Serapis through historic time, and its possible correlation with volcanic activity in the neighbourhood (after Parascandola, 1952

made a complete circuit of the crater wall, and from its west and north sides looked across the Valle dell'Inferno at the lower arcuate ridge of Monte Somma. This is all that remains of the older and larger crater which preceded Vesuvius. Its centre lay about a quarter of a mile north of that of the present volcano, and its southern and western walls were completely blown away in the eruption which extinguished Pompeii. This sudden and violent activity followed more than 1000 years of quiescence.

The party returned to the coach which then descended the mountain. Halts were made to examine the lava flows of 1858 and 1895, displaying excellent examples of 'ropy' surfaces (see Plate 11 B). Loose blocks of pumice and of metamorphic rocks (presumably from Monte Somma) were also collected. The party then returned to Naples.

### Wednesday, 29 and Thursday, 30 September

The party left Naples late the following morning after further visits to the Marine Biological Station. The following day a three-hour wait in Paris enabled them to indulge in some of the gastronomic and other delights of that city, before catching the boat-train for Calais. As the ship left Calais harbour for a stormy sea, Alderman W. P. D. Stebbing proposed a vote of thanks to the Secretary and Mrs. Ager for their work in connection with the excursion. This was carried by the assembled members. Eventually the party broke up at Victoria Station at about 8 p.m.

## ACKNOWLEDGMENTS

The author would like to record his thanks to Dr. A. Azzaroli and to his colleagues Dr. J. Watson and Dr. J. Sutton for their critical reading of the manuscript of this report. Also he is indebted to Professor J. H. Taylor, Mr. F. H. Broadhurst and Mr. A. V. James for the loan of photographs for the plates, and to Mr. J. A. Gee for their reproduction. Professor G. Merla, Dr. A. Azzaroli and Dr. A. Parascandola kindly gave permission for the use of certain text-figures from their publications. Dr. W. E. Swinton gave considerable help by providing information about the Naples area.

Finally the author is very grateful to his wife for her help, both on the excursion and in the preparation of this report.

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* These papers, which describe areas visited by the party, were published subsequent to the field meeting and to the writing of this report (D.V.A.).

# Field Meeting to examine the Great Oolite Series of Oxfordshire

**7 August 1955**

Report by the Director: W. S. McKERROW

Received 15 August 1955

TWENTY-NINE MEMBERS attended the meeting. The party left London by motor-coach at 9 a.m. and arrived in Oxford two hours later. The first exposures examined were at Crawley Road Quarry, Witney (354108), where permission for access had been given by Mr. C. Haines, The Garage, Witney. Here Wychwood, Bradford and Kemble Beds were seen overlying uppermost White Limestone (Arkell, 1947, pp. 49–50).

In the north-west part of the quarry the Bradford Fossil Bed was seen to consist of three feet of marly limestone crowded with fossils. This bed occurs over a large area of Gloucestershire and Oxfordshire, but is missing at many localities (including the south-east end of Crawley Road Quarry). Its wide extent and its abundance of well-preserved fossils suggest that it is a condensed deposit; probably its absence at some localities is due to subsequent erosion. There can be little doubt that it represents a single time-plane, and is thus a reliable aid in the correlation of the higher beds of the Great Oolite Series.

Towards the south-east end of the quarry both the Wychwood Beds and the Kemble Beds show lateral changes between limestones and clays. On this account correlation of these beds in terms of lithology alone is clearly unreliable. A pit about two feet deep, dug in the floor of the quarry at its eastern end, reveals the Witney Coral Bed—a limestone with lignite and drifted valves of *Epithyris oxonica.*

From Witney the party travelled westwards along the main road to Burford. An abandoned meander of the River Windrush, floored by gravels of the Summertown Terrace, was observed near Asthall. Proceeding north from Burford, the next halt was at the Milton quarries (visited by kind permission of Mr. L. G. Paget, The Downs Farm, Milton under Wychwood). In these quarries (257158) the Taynton Stone was worked from the fourteenth to the sixteenth century, and again in the nineteenth century (Arkell, 1947*a*, p. 64), but at present only the overlying Hampen Marly Beds and lowest White Limestone are to be seen. On leaving Milton quarries, the route lay along the crest of the Great Oolite scarp south of the Evenlode valley and north of the woods which are the remnants of Wychwood Forest. Extensive views were obtained from this road: northwards towards the Vale of Moreton and southwards over the Corallian and Upper Greensand scarps to the Chalk of the Berkshire Downs.

After lunch at Charlbury, the party went down the Evenlode valley towards Stonesfield. The Stonesfield Slate occurs in a very limited area round the village (Arkell, 1947, p. 150) and was excavated (between the sixteenth century and 1909) mainly by vertical shafts cut through the overlying Taynton Stone. It is only from old tip heaps that the slate is now obtainable. The party collected from one such heap which lies north of the road west of Stonesfield (382172).

On moving southwards the party crossed the Evenlode at Ashford Mill, where incised meanders were pointed out, and noted how much deeper and narrower the valley is at this point than it is at Charlbury. The gravels of the hundred-foot terrace were seen at Long Hanborough, after which the party visited Long Hanborough Station Quarry (436142) by permission of Messrs. Benfield & Loxley Ltd., 106 Bullingdon Road, Oxford. Here the Lower Cornbrash was seen to rest on a clay, which (in the absence of the Bradford Beds) has been assigned to the Kemble Beds by Arkell (1931, p. 586) and to the Wychwood Beds by Richardson (Richardson *et al.*, 1946). Below this occur current-bedded limestones which are worked for building stone (known locally as 'Bladon Stone'). These limestones have been used for the walling of the Geology Department and many other new buildings in Oxford (see Arkell, 1947*a*, p. 114). They are assigned to the Kemble Beds and the top of the White Limestone; the junction between the two (about three feet above the present floor of the quarry) is marked by a lignite-bearing marly limestone.

In Tolley's New Quarry, Bladon (450150), one mile to the north-east, Arkell (1947, p. 56) records the reappearance of the Wychwood Beds which consist of eight feet of thin-bedded limestones and clays. Below this horizon, the Kemble Beds (five feet of clay overlying eight feet of limestone) resemble the beds seen at Long Hanborough Station Quarry except that the limestones are not strongly current-bedded. The White Limestone composes the lowest thirteen feet of the quarry. At the top it includes a lignite-bearing clay, as at Long Hanborough, but four feet below this level is a bed largely made up of drifted *Epithyris* shells and including some corals. The party spent some time collecting from this last horizon. Arkell (1947) refers to this as the Witney Coral Bed (i.e. the bed seen below the floor of Crawley Road Quarry, Witney). However, similar beds containing drifted brachiopod shells are often seen to die out laterally in the Great Oolite of Oxfordshire. Moreover, they are known to occur at many horizons. For these reasons they are not of the same use to the stratigrapher as is a condensed deposit like the Bradford Fossil Bed. Thus it would appear to the writer that the *Epithyris* and coral bed at Bladon is not necessarily at exactly the same horizon as the Witney Coral Bed.

From Bladon the party went north-eastward towards Kirtlington. After crossing the road from Oxford to Woodstock, views were obtained of the Corallian and Chalk scarps to the south. On passing the large exposure in the Shipton Cement Works' quarry, the attention of the party was drawn to the incised meanders of the Cherwell. The downcutting in this valley, as in the Evenlode Valley, is associated with river terraces; a small pit in the hundred-foot terrace, west of Kirtlington, was briefly noted (497200). The party then walked westwards to Kirtlington Old Cement Works (495200). This quarry had been visited by the Association three years previously (McKerrow & Baden-Powell, 1953). Considerable collecting was carried out by members in the Wychwood and Kemble Beds and in the White Limestone, and one member obtained a fine specimen of *Clydoniceras* from the Lower Cornbrash. It is of interest to note that none of the three *Epithyris* beds at Kirtlington is at the same horizon as the *Epithyris* bed at Bladon (Arkell, 1947, p. 56).

After tea at Woodstock, the President, Dr. L. R. Cox, proposed a vote of thanks to the Director and to the Secretary, Miss S. Feinsilber. Following a brief visit to Oxford, the party left for London at about 7 p.m.

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# Field Meeting in the Central Cotswolds

**3–5 June 1955**

Report by the Director: D. V. AGER

Received 30 September 1955

IN SPITE of a national railway strike, thirty-three members and friends of the Association met at Stroud during the first week-end in June for a two-day study of the Lower and Middle Jurassic rocks of the neighbourhood. The primary aim of the excursion was a demonstration of lateral variation in the Inferior Oolite and higher Liassic rocks of the Cotswolds between Wotton-under-Edge and Cheltenham. Most of the exposures studied had been previously visited by the Association, but some of the Liassic pits—notably Robin's Wood Hill—have never been so visited, although the omission was noted long ago by Richardson (1910*a*, p. 339).

## Saturday, 4 June

The first day was devoted to the area south of the headquarters at Stroud. In a coach the party proceeded southwards on the Nailsworth road, and then across the remarkably flat limestone plateau to Combe Hill on the escarpment above Wotton-under-Edge. Here the first halt was made at the 'Waterworks Quarry' (map reference ST 767943) where the Upper *Trigonia* Grit of the Upper Inferior Oolite (Vesulian) was seen resting on the Lower Freestone of the Lower Inferior Oolite (Aalenian). This was mainly below the older section described here by Richardson (1910*b*, pp. 103–4). At this locality the Vesulian beds proved to be highly fossiliferous, with *Trigonia costata* (Sowerby), *Acanthothyris spinosa* (Schlotheim), *Tricites* sp., and many other characteristic fossils. The top of the underlying bed was conspicuously bored, marking the position of an important non-sequence.

The party then continued down the hill into Wotton-under-Edge, and at the north end of the village examined the fine sections beside the old London road up Wotton Hill. These sections have also been described in detail by Richardson (*op. cit.*, pp. 104–6). In the lower of the two sections (map reference ST 753938), the Cephalopod Bed with its abundant ammonites and belemnites, was seen to be resting on the Cotswold Sands, which were also displayed in an entrance-way farther down the lane. Here the section may be summarised as follows:

| | | | ft. | in. |
|---|---|---|---|---|
| *scissum* beds | (f) | Massive limestone with *Tmetoceras scissum* in the upper beds, and *Lioceras opaliniformis* in the lower | 5 | 6 |
| Cephalopod Bed | (e) | Marly beds with *Homoeorhynchia cynocephala* | 3 | 6 |
| | (d) | Ironshot marls, highly fossiliferous with *Dumortieria* sp. in the upper beds, and *Grammoceras dispansum* in the lower | 6 | 4 |
| | (c) | Massive, somewhat ironshot limestone, with marly partings | 1 | 8 |
| | (c*) | Coarsely ironshot marl | 1 | 0 |
| | (b) | Massive ironshot oolite, highly fossiliferous, with *Grammoceras striatulum* | 1 | 2 |
| Cotswold Sands | (a) | Yellow micaceous sands, massive, with calcareous doggers ... seen to about | 20 | 0 |

The Director reminded the party of the diachronism of the sands at the bottom of the section, first clearly demonstrated in a classic work by S. S. Buckman (1889). The Cotswold, Midford, Yeovil and Bridport Sands, though lithologically similar, represent a belt of deposition which moved progressively southwards during Toarcian and Aalenian times.

Farther up the hill the party visited a quarry in Inferior Oolite limestones (map reference ST 754940). This was also still very much as described by Richardson (*loc. cit.*), and may be summarised as follows:

| | | ft. | in. |
|---|---|---|---|
| Vesulian | Upper Coral Bed: White shelly rock in lenticular masses with corals | 0 | 10 |
| | Dundry Freestone equivalent: Limestone, hard, shelly, slightly iron-speckled | 0 | 2 |
| | Upper *Trigonia* Grit: Limestone, hard grey above, rubbly below, top bored | 2 | 6 |
| Aalenian | Lower Freestone: Limestone, coarsely oolitic, bored upper surface, rubbly bands near base | 17 | 9 |
| | Pea-Grit horizon: Rubbly limestone | 0 | 6 |
| | Lower Limestone: Limestone, massive ... seen to about | 18 | 0 |

Again the Director drew special attention to the evidence of a non-sequence between the Vesulian and Aalenian deposits. The party then returned to the coach and drove northwards along the marked platform formed by the Middle Lias Marlstone Rock-bed which lies below the main Inferior Oolite escarpment. This was particularly clear at Nibley Knoll, from where a distinct view was obtained of the Severn estuary and the hills beyond. The Palaeozoic inlier of Tortworth could be seen in the foreground, and the Director commented on the narrowness of the Lias and Trias outcrops at this point, when compared with their widths farther north. This is a reflection of the thinning of the Mesozoic strata towards the Mendip axis.

As the coach approached the westerly-projecting spur of Stinchcombe Hill, the Director pointed out the narrow ridge that forms its only connection with the main escarpment. At the foot of the hill, the side-road on the south-west side of the Yew Tree Inn was taken for a short distance. The hamlet here—known as 'The Quarry'—stands in what was once an extensive working in the Marlstone Rock-bed. A small part of the face of this old quarry was examined in the field beyond Newent Quarry House (map reference ST 735994). Here there is exposed about ten feet of Marlstone Rock-bed, in its usual form of a highly fossiliferous ferruginous limestone. The small rhynchonellid *Gibbirhynchia micra* was especially abundant in the lower part of the face, and was first described from this locality (Ager, 1954). A specimen of the zonal ammonite—*Pleuroceras spinatum* (Bruguière)—though not previously known from here, was found by a member of the party. It was recalled that the so-called 'Transition Bed' of the Midlands, with *Tiltoniceras acutum* (Tate), was once recorded above the Marlstone Rock-bed at Dursley. Lunch was taken in Dursley, a short distance farther along the main road.

After leaving Dursley, the outliers of Downham Hill and Cam Long Down were seen on the left, followed by extensive views across the Severn Valley to May Hill, the Malverns and beyond. The party left the coach again by Selsley Hill Farm, at the south end of Selsley Common, and spent some time examining the various quarries described in detail by Richardson (*op. cit.*, pp. 123–7), in pursuance of Witchell's earlier work. The following section was examined at 'Leigh's Quarry', at the south end of the hill (map reference SO 826026):

| | | ft. | in. |
|---|---|---|---|
| *Clypeus* Grit | Limestone, somewhat flaggy, *Stiphrothyris* spp., '*Rhynchonella*' *hampenensis*, etc. ... ... ... | 5 | 0 |
| | Limestone ... ... ... ... ... ... | 1 | 3 |
| | Limestone, top bored ... ... ... ... about | 2 | 2 |
| | Limestone with irregular under surface ... ... | 0 | 8 |
| | Limestone, grey-brown ... ... ... ... ... | 0 | 9 |
| | Limestone ... ... ... ... ... ... | 0 | 7 |
| | Limestone, rubbly ... ... ... ... ... | 2 | 6 |
| | non-sequence | | |
| Upper *Trigonia* | Limestone, very shelly, with a layer of oysters on top ... | 0 | 10 |
| | Irregular pale-brown, non-oolitic limestone and shaly marl ... ... ... ... ... ... about | 0 | 6 |
| | Ragstone ... ... ... ... ... 1 ft. 6 in. to | 2 | 0 |
| | Rubbly limestone ... ... ... ... ... | 0 | 6 |
| | Ragstone (='Gryphite Grit' of Witchell) 1 ft. 6 in. to | 2 | 1 |
| | non-sequence | | |
| Upper Freestone | Limestone, white, oolitic, top bed conspicuously bored | 4 | 2 |
| Oolite Marl | Limestone, rubbly, whitish ... ... ... ... | 1 | 10 |
| | Marly parting, small sponges ... ... ... ... | 0 | 0½ |
| | Limestone, *Plectothyris fimbria*, *Globirhynchia* spp. about | 1 | 3 |
| | Marl with brachiopods ... ... ... ... ... | 0 | 2 |
| Lower Freestone | Limestone, massive, white, oolitic ... seen to | 13 | 0 |

It was observed that additional beds of the Aalenian (i.e. the Upper Freestone and Oolite Marl) present here, had been absent at Wotton Hill. This conforms to the general theory of an Aalenian basin in the Cotswold region, the deposits of which were planed off by pre-Vesulian erosion.

The party then walked to the tumulus at the top of the hill, from which the Director pointed out geomorphological features of the surrounding countryside, including the three terraces which are recognised on either side of the River Frome west of Stroud. To the north-east was seen the adjacent hill of Rodborough Common, with its Victorian castle. Though not visited on this excursion, it is noteworthy that exposures on this hill show the presence of the Lower *Trigonia* Grit and *Buckmani* Grit of the Middle Inferior Oolite (Bajocian s.s.). Their presence marks the edge of a synclinal trough—the Painswick syncline—in which a small thickness of these beds is preserved on account of gentle folding at the end of Bajocian times, prior to the Vesulian transgression.

Just north-east of the tumulus, the party noted a very shallow exposure (Witchell's Quarry No. 1, mentioned by Richardson); this showed rubbly limestone probably belonging to the Upper *Trigonia* Grit. A larger quarry, north of this, beside a corrugated iron shed, was Witchell's Quarry No. 2. This shows the following succession, all of which appears to belong to the Freestones and Oolite Marl horizon (which are often not clearly separable):

| | | ft. | in. |
|---|---|---|---|
| (d) Flaggy oolite, becoming more massive with shaly partings below ... ... ... ... ... ... | seen to | 13 | 0 |
| (c) Massive oolitic limestone with *Plectothyris fimbria* and other fossils ... ... ... ... ... ... ... ... | | 2 | 2 |
| (b) Shale band ... ... ... ... ... ... ... ... | | 0 | 6 |
| (a) Massive oolitic limestone ... ... ... ... | seen to | 1 | 0 |

The flaggy oolite at the top of this section was observed to be false-bedded, and the possibility was discussed of deducing a prevailing current direction for this horizon from a large number of such observations. A fossiliferous band at the top of bed (d) yielded a good fauna including the characteristic Aalenian terebratulid *Plectothyris fimbria* (Sowerby). The party left this quarry by the old trackway which leads down the north side of the hill. To the left of this track is Witchell's Quarry No. 4, which still shows the following section:

| | | | ft. | in. |
|---|---|---|---|---|
| Pea Grit | Limestone, rather flaggy, pisolitic ... ... ... | | 3 | 0 |
| | Brownish marly deposit with loose pisoliths, *Pseudoglossothyris simplex*, *Rhynchonelloidea*(?) *subangulata*, *Stomechinus* spp. etc. ... ... ... | | 1 | 0 |
| | Rubbly pisolitic rock ... ... ... | 2 ft. 6 in. to | 3 | 6 |
| | Brown marly layer with pisoliths ... ... ... | | 0 | 2 |
| Lower Limestone | Limestone, even surface above, uneven below ... | | 2 | 4 |
| | Limestone, small gastropods ... ... | seen to | 17 | 0 |

This was the first section in which the highly distinctive Pea Grit was seen by the party. Southwards it diminishes to less than a foot in thickness at Uley Bury and cannot be distinguished thereafter, though at Wotton Hill Richardson attributed six inches of rubbly limestone to this division (see above, p. 356). Besides being notable for its pisolitic lithology, the Pea Grit is also remarkable for the variety and abundance of its fauna, including echinoids.

As the party descended the north side of Selsley Hill to the road, the Director pointed out Witchell's Quarry No. 6, beyond a stone wall. Now it is used as a rubbish dump. Here, again the Lower Freestone is seen, dipping fairly steeply on account of a local fault. Hereabouts this division has been called the 'Dapple Beds' on account of its content of white oolite pebbles, produced by penecontemporaneous erosion.

After rejoining the coach near the New Inn, the party proceeded northwards to the main road near Dudbridge. The middle terrace of the three Stroud terraces was then followed through Ebley to Jeffries Brick Works near Stonehouse (map reference SO 816050). Here a complete section of the Middle Lias was seen in an excellent exposure which appears to have been overlooked by geologists. At the top of the face the Marlstone Rock-bed is again present, but here it is in the form of a buff, fine-grained sandstone. The Director expressed his view that this facies replaced the usual ferruginous limestone (as seen near Dursley) between Stroud and Cheltenham, and probably represents an inshore deposit. He suggested that the palaeogeographical reconstructions usually made for the Lias are founded on the evidence available for the lowermost zones, when the sea was more extensive than it was at the time of deposition of the Marlstone Rock-bed.

At the base of the Rock-bed there is a nodule bed, about six inches thick, comparable to that developed at the same level throughout the Midlands. Further evidence supporting the postulated correlation was the occurrence of occasional specimens of *Gibbirhynchia micra* in the lowermost two or three feet.

Bands of ferruginous limestone occur lower down in the section. They are of the same general appearance as the Marlstone Rock-bed elsewhere, but without the characteristic brachiopods, and yielding a small species of *Amaltheus*. Therefore these beds are attributed to the *margaritatus* Zone. The 'rock' bands were seen to have been broken up into a series of tilted blocks, clearly related to the present slope of the ground, and presumably attributable to a period of perma-frost conditions during the Pleistocene. It is proposed to give a more detailed description of this section, and the next, in a subsequent work on the Lias of the Vale of Gloucester.

After collecting a large fauna at Jeffries' pit, the party went on to Stonehouse for tea. Finally, a visit was paid to the large brick-pit of the Stonehouse Brick and Tile Company by Stonehouse Station. Here the Middle

Lias was seen, as before, but in a more inaccessible position at the top of a steep face. It is underlain by clays and argillaceous limestones of the *davoei* Zone, at the top of the Lower Lias. Species of *Androgynoceras* and *Lytoceras* are common in these lower beds, together with a large fauna of lamellibranchs. An excellent specimen of the 'brittle-star' *Ophioderma gaveyi* Wright was found by one member of the party in a loose block.

A few members scrambled to the top of the section east of the main face, and again saw the Marlstone Rock-bed in its sandy facies with a basal nodule bed and *Gibbirhynchia micra*. The more energetic members also went on to the summit of Doverow Hill, where a large and overgrown quarry shows the lower divisions of the Inferior Oolite, here apparently resting directly on the Cotswold Sands. The party then gathered once more in the station approach and returned to Stroud.

After dinner, the majority of the members present visited the Cowle Museum, Stroud, which was specially opened for the purpose. There they were welcomed by the curator, Mr. L. Walrond, and spent some time examining geological and other specimens collected in the neighbourhood. A special attraction was a large number of reptilian bones from the Chipping Norton Limestone. Before leaving, the president (Dr. L. R. Cox) expressed the Association's thanks to Mr. and Mrs. Walrond for their kindness in entertaining the party.

### Sunday, 5 June

The second day was devoted to an examination of the area extending north of Stroud as far as Cheltenham. The route lay up the Painswick Valley past a road cutting in the Middle Lias and through the lovely village of Painswick.

Just north of the Royal William Hotel, at the south end of Prinknash Park, there was a short halt to examine a small exposure of the Gryphite Grit of the Middle Inferior Oolite (Bajocian s.s.). Though now almost overgrown, this was the only convenient exposure on this route at which to demonstrate the presence of the middle division in the Painswick syncline. Several specimens were seen of the characteristic lamellibranch—*Gryphaea sublobata* (Deshayes)—and vertical borings were noted, suggesting the proximity of the sub-Vesulian unconformity.

The coach then carried the party to Birdlip where the Roman road from London to Gloucester—Ermin Street—descends the Cotswold escarpment. Here a road-cutting was examined behind the Royal George Hotel, showing once again Vesulian rocks resting directly on the Upper Freestone of the Aalenian. The following section was examined:

| | | ft. | in. |
|---|---|---|---|
| *Clypeus* Grit | Rubbly, white to golden oolite, very fossiliferous, *Clypeus ploti*, *Stiphrothyris tumida*, etc. ... | 14 | 6 |
| | parting | | |
| Upper *Trigonia* Grit | Massive oolite, poorly fossiliferous ... ... | 4 | 6 |
| | non-sequence | | |
| Upper Freestone | Massive golden oolite, oyster-covered upper surface, otherwise unfossiliferous ... seen to | 7 | 6 |

The lower beds represent the core of the Birdlip anticline, folded and planed off before the Vesulian transgression. The village of Birdlip is built on the *Clypeus* Grit and specimens of the characteristic echinoid are to be found in the cottage gardens.

A short distance north of Birdlip the coach stopped at Barrow Wake, a spot famous for its extensive views over the Vale of Severn and the hills of the Welsh Borderland. In the quarry to the east of the road is a section in strongly false-bedded Upper Freestone. The Director drew the attention of the party to an anomalous feature at the top of the quarry, where a thin but wide slice of unbroken limestone overlies a small thickness of brashy soil, and is separated from the main rock face. Mr. D. J. Shearman has suggested that, under peri-glacial conditions, melting of the top few feet of ground-water may have caused this thin slice of limestone to slide down the dip slope for a short distance. Comparable phenomena are known in northern Canada at the present day.

After admiring the view from here, the party moved on to Tuffley's Quarry, near the Air Balloon public house (map reference SO 932159), where the excellent section is still much as it was when described by Richardson (1904, p. 110), and shows Bajocian beds up to and including the *Buckmani* Grit beneath the sub-Vesulian unconformity. These beds are preserved in the complementary Cleeve Hill syncline on the north-east side of the Birdlip anticline.

Before lunching at the 'Air Balloon', the party descended Crickley Hill for a short distance to examine sections in the Pea Grit north of the road (map reference SO 930160). About 40 ft. of highly fossiliferous Pea Grit was seen to overlie the Lower Limestone. Corals were obtained from the thin coral bed at the top of the Pea Grit at this locality.

After lunch, the coach took the party to the hairpin bend north of Ullenwood, where a dip fault breaks the line of the escarpment. The party then climbed the southern flank of Leckhampton Hill, briefly examining *en route* the large quarry in Lower Freestone and Pea Grit opposite Salterley Grange Sanatorium. At the top of the hill the party walked across a '*Gryphaea* pavement' on the floor of an extensive old quarry. This surface, covered with specimens of *Gryphaea sublobata*, represents the Gryphite Grit of the Bajocian, which is almost immediately overlain by the Upper *Trigonia* Grit on this southern side of the hill. A small 'stack', left by the quarrying, clearly displays the sub-Vesulian unconformity (map reference SO 951180). The beds above this yielded abundant specimens of *Trigonia costata*, together with *Acanthothyris spinosa*, *Parkinsonia parkinsoni* (the zone ammonite) and other fossils. The actual contact between the two divisions is encrusted with oysters and the lower bed is extensively bored by marine organisms.

After descending the hill again, the party walked round below the westward-facing cliffs, noting the false-bedding in the freestones and the famous landmark of the 'Devil's Chimney'. The section in the old Leckhampton Quarry (map reference SO 949186) is too well known to require further description (see Richardson, 1904, pp. 79–80). The softer beds of the Aalenian are now much obscured by fallen material, but most of the best-known fossils were found. The party then rejoined the coach on the main road and drove to the equally famous Battledown Brick-pit on the eastern outskirts of Cheltenham (map reference SO 960218). Here an abundant fauna of ammonites, lamellibranchs and brachiopods was collected from the *ibex* and *davoei* zones at the top of the Lower Lias.

The route then lay south-westwards from Cheltenham, past the outlier of Churchdown (or Chosen) Hill, and by-passing Gloucester to reach the nearby outlier of Robin's Wood Hill. At Tuffley, on the western flank of this hill, the party examined the excellent section of Lower and Middle Lias exposed in the brick-works (map reference SO 836149). This section, though one of the best in the region, has never been described in detail. A particularly interesting note about it was published by the Rev. A. Watts (1928) in an account of an excursion by the Cotteswold Naturalists' Field Club. He recorded a supposed evolutionary sequence of ammonites in the Lower Lias here, ranging from involute spinose sphaerocones below, to evolute non-spinose serpenticones above. He explained this trend as being towards 'safety in swiftness rather than armour'. Though he misidentified the ammonites in question, there is no doubt, on the evidence afforded by both the present section and the specimens named by Watts in the Stroud Museum, that he was dealing with the *Liparoceras–Androgynoceras* lineage. Therefore, without realising it, Watts reversed what was then the standard evolutionary (cum recapitulatory) story for the Liparoceratidae, and anticipated by ten years the classic work of Spath in this matter (1938).

Though more may have been visible in 1928, when it was studied by Watts, the present section is as follows:

| | Bed | ft. | in. |
|---|---|---|---|
| *spinatum* Zone | 17. Soft, buff, micaceous, massive, fine-grained sandstone, weathering into large rounded doggers in places; the top 3 to 4 ft. flaggy and highly fossiliferous, the lowest 6 in. nodular with occasional specimens of *Gibbirhynchia micra* about | 18 | 0 |
| | ? | | |
| | 16. Grey shales ... ... ... ... ... ... | 16 | 8 |
| *margaritatus* Zone | 15. Ferruginous limestone, nodular in lower part, *Amaltheus* sp. ... ... ... ... ... | 1 | 6 |
| | 14. Grey shales ... ... ... ... ... ... | 21 | 0 |
| | 13. Ferruginous limestone, nodular at base, with *Amaltheus* spp. and a large fauna of lamellibranchs and belemnites ... ... ... ... | 1 | 10 |
| | ? | | |
| | 12. Grey shales ... ... ... ... ... ... | 10 | 0 |
| | floor of upper quarry | | |
| (age uncertain) | 11. Grey shales ... ... ... ... ... ... | 2 | 0 |
| | 10. Ferruginous band, lower part weathering white ... | 1 | 0 |
| | 9. Grey shales with bands of ferruginous nodules, especially in the top 6 ft.; prominent nodule bands 15 ft., 24 ft. and 48 ft. below top about | 53 | 0 |
| *davoei* Zone and *ibex* Zone (pars) | 8. Ferruginous band, highly fossiliferous, with *Androgynoceras* sp. and '*Rhynchonella*' gen. et sp. indet. ... ... ... ... ... | 0 | 4 |
| | 7. Sandy grey shales ... ... ... 1 ft. 6 in. to | 2 | 0 |
| | 6. Prominent band of hard sandy shales 2 ft. 4 in. to | 4 | 6 |
| | 5. Grey shales ... ... ... ... ... about | 16 | 0 |
| | 4. Prominent band of ferruginous nodules ... 6 in to | 1 | 0 |
| | 3. Grey shales with nodules, especially in lower part ... ... ... ... ... about | 48 | 0 |
| | 2. Grey argillaceous limestone, highly fossiliferous, with *Androgynoceras* spp., *Oxytoma*, etc. ... | 1 | 1 |
| | 1. Grey shales with nodules ... ... seen to | 10 | 0 |

The *spinatum* Zone again shows its sandy facies at Robin's Wood Hill, as it does at Churchdown Hill, farther north, where it was described in detail by the Rev. F. Smithe in a series of papers written during the latter part of last century. Once again the nodule bed with *Gibbirhynchia micra*, at the base of the Rock-bed, serves as a useful guide. Several members climbed the lower face of shales (or shaly clays) to inspect the ferruginous band (bed 8 above) which yielded a large and varied fauna.

Though time did not permit the examination of the higher strata on the hill, the Director indicated that here the Upper Lias takes the form of unfossiliferous silts and silty clays, with no representative of the true Cotswold Sand facies as seen farther south. Only a very small capping of lowermost Inferior Oolite is present beneath the trigonometrical point at the summit.

When the party had reassembled in the coach, after leaving the brick-pit, the president (Dr. L. R. Cox) thanked the Director and Mrs. Ager, on behalf of the Association, for organising the excursion. A brief halt was made on Scottsquar Hill during the ride back to Stroud, to admire the large quarry in golden freestone, near where it is being worked at present for repairs to Gloucester Cathedral. At Stroud, members of the party dispersed.

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# Demonstration at the Department of Geology, King's College, London

### 5 March 1955

Report by the Head of the Department: J. H. TAYLOR

Received 17 May 1955

IN WELCOMING the party, Professor J. H. Taylor referred to previous visits of the Association to King's College in 1921, 1935 and 1944. On the present occasion a number of exhibits had been set out to illustrate the two main aspects of work in the Department: undergraduate teaching and post-graduate research.

Dr. A. K. Wells exhibited a selection of the material used in the teaching of crystallography and mineralogy, including quartz crystals showing special features, together with some cut and polished gemstones and their raw materials from the collection of the late Professor W. T. Gordon. Also he displayed rock specimens and photographic enlargements to illustrate work in progress on contact relations between granite and more basic rocks in the north of Jersey.

Dr. R. W. D. Elwell displayed rock specimens from north-western Mayo. The succession, shown on a map accompanying the exhibits, includes micaceous and feldspathic quartzites, schists of high grade and a boulder bed of the type familiar in Donegal. A migmatite zone, in which granite-gneisses and hornblendic and biotite-rich schists occur, occupies much of the ground. Epidiorite sills occur at intervals and their progressive reconstitution under regional metamorphism was demonstrated by a series of thin sections showing intermediate stages in the change from essentially doleritic rock to lineated hornblende-schist.

Mr. A. J. R. White demonstrated a map of the Palmer area, near Adelaide, South Australia, illustrating field work done on the problem of the origin of certain granites and granite-gneisses. These are believed to include both metasomatic and intrusive types. Specimens collected across the strike of the granite-gneiss and adjacent schists were exhibited, with petrofabric diagrams illustrating the similarity of the biotite fabric throughout. The metasediments surrounding the granites include calc-silicate rocks containing abundant scapolite.

Dr. J. E. Prentice exhibited maps and specimens illustrating the stratigraphy and structure of the Culm measures of north-west Devonshire.

The intense isoclinal folding is revealed by mapping, which shows a series of close E.–W. folds dissected by very numerous NW.–SE. and NE.–SW. faults. Various sedimentary structures, found at one horizon, were displayed in hand specimens. Another exhibit showed the results of studies of the larger productids of the Carboniferous.

Dr. C. G. Adams showed a representative collection of foraminifera from the Upper Lias of North Lincolnshire. The wide range of variation met with in the megalospheric forms of many Lagenid genera and species was illustrated, in the cases of *Falsopalmula deslongchampsi* (Terquem) and *Marginulina prima* d'Orbigny, by means of photographs and distribution diagrams. Specimens showing the difference in development of identical genera and species, when traced from the clays of the upper part of the Middle Lias to the *tenuicostatum* zone of the Upper Lias, were also displayed.

Mr. J. G. Wynd contributed a series of photographs and sections illustrating the results of sectioning Albian brachiopods with the Croft Parallel Grinder. Sectioned specimens of the genera *Rectithyris*, *Neoliothyrina* and *Concinnithyris* showed the differences in their internal structures. Pictographs and scatter-and-frequency-diagrams resulting from the study of these brachiopods were also displayed, together with a model representing a 'scatter' in three dimensions.

Mr. R. G. Thurrell exhibited field maps and structural diagrams covering an extensive area of the Lower Cretaceous outcrop in the South Lincolnshire Wolds, and demonstrated the lateral changes in lithology and thickness shown by mapping. Well-preserved boreal ammonites of the genera *Subcraspedites*, *Simberskites* and *Dichotomites* from the Spilsby Sandstone and terebratulid brachiopods from both Claxby and Fulletby Beds were shown, as well as newly discovered fauna of brachiopods and fragmentary ammonites from the Tealby Limestone horizon at Cawkwell.

Mr. B. J. Williams had arranged an exhibit to show the characteristic faunal assemblages present in the Lower Ludlovian rocks of the south-west limb of the Ludlow anticline. Techniques used as aids to the study of the morphology of the graptolites were illustrated (a) by serial sections of a specimen of *Monograptus dubius* prepared with the Croft Parallel Grinder, and (b) by specimens representing stages in the isolation of the fossils by dissolving the matrix in strong acid and using Marco resin as an embedding medium.

After tea Dr. A. K. Wells demonstrated a collection of anorthosites and migmatitic gneisses illustrating some aspects of the geology of the fjord country of south-west Norway. These specimens were complementary to a series of lantern slides, illustrating the scenery of this area, which were shown and accompanied by a commentary on their geological background.

Professor J. H. Taylor exhibited a geological map of the west central

Weald where over seventy-five square miles of country in the region of East Grinstead and Haywards Heath have been mapped on the six-inch scale by Honours students from the Department. Various textures and structures present in the Hastings Sand were illustrated by specimens and photographs. With the co-operation of members of the Lyell Club, a detailed study of the area is in progress.

Finally the party had an opportunity of seeing something of the work done by the Laboratory Technicians in the preparation of thin sections and polished mounts.

After the President had thanked the various demonstrators and had referred appreciatively to the long-standing connections between the Association and King's College, and especially to the work done from 1924 to 1932 by Dr. A. K. Wells as Editor of the *Proceedings*, the party dispersed.

# The Use of Sugar Solution in the Differentiation of the Internal Structures of Upper Chalk Brachiopods

by ELLIS F. OWEN

*Department of Geology, British Museum (Natural History)*

Received October 1954

IN STUDYING TRANSVERSE SECTIONS of fossil brachiopods it is often necessary to differentiate between the shell and internal structures, on the one hand, and the infilling on the other. For this purpose, a method of heating brachiopods to calcine their shells and brachial skeletons was described by Muir-Wood (1934) and is now used widely for both Palaeozoic and Mesozoic specimens. In the case of brachiopods from the Upper Chalk, however, this method cannot be used to advantage since the matrix does not allow of differentiation and the sectioning of such specimens gives poor results. Hitherto, in order to examine their internal structures it has been necessary to employ the rather tedious and somewhat risky process of dissection by means of a mounted needle or dental engine, as described by Sahni (1929).

Experimental work has been carried out in the Department of Geology of the British Museum (Natural History), and as a result the following technique has been developed for differentiating Upper Chalk brachiopods.

## TECHNIQUE

A forty per cent solution of ordinary cane sugar in tap-water is prepared. A complete uncrushed brachiopod is then selected from a locality where the chalk matrix is fine without being highly compressed. Part of the shell forming the anterior portion of the specimen is removed in order to expose an area of internal matrix. Then the specimen is placed in a suitable receptacle containing sufficient sugar solution to cover it completely. The solution is brought to the boil slowly, thereby allowing air expelled from the matrix to be replaced by sugar solution. The specimen is allowed to remain in the latter for at least twenty-four hours. Next, the brachiopod is removed from the solution and allowed to dry before being heated to redness in a bunsen flame. The intense heat will calcine both the exterior shell and the internal structures and at the same time reduce the absorbed sugar solution to carbon. The effect of this reduction is to colour the matrix dark brown while leaving the surrounding shell and internal structures white.

$$C_{12}H_{22}O_{11} + \text{heat} \rightarrow 12C. + 11\ H_2O$$

$$\text{i.e.}\quad \text{sugar} + \text{heat} \rightarrow \text{carbon} + \text{water}$$

Results obtained by the application of this technique to both large and small specimens are surprisingly good, but the following points are worthy of special care:

(a) specimens possessing an *altered* shell give better results than those which are well preserved.

(b) either heating too rapidly, or heating before the matrix is properly dry, may cause the loss of the brachiopod through the production of a minor explosion.

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